CHAPTER 2

AN ASSESSMENT OF SEVERE AND SUSTAINED DROUGHT IN THE COLORADO RIVER BASIN

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CHAPTER 2

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Introduction

Discussed in this chapter are the methodology for drought characterization and analysis, and data on severe, sustained drought dimensions relative to the projected demand for water in the Colorado River basin.

Given that the Colorado River system has a storage capacity over four times as great as its average annual natural runoff, and an elaborate system of perfected laws governing allocation and system operation, it might well appear that the Colorado is an inappropriate system in which to test institutional responses to severe, sustained drought. However, at least two factors justify closer examination. The first concerns hydrologic reconstructions of unimpaired flows at Lee Ferry, Arizona, based on tree-ring analysis. These reconstructions indicate that droughts much more severe than those indicated from conventional streamflow measurements have occurred in the basin's recent past. The second factor involves possible increases in the probability, characteristics, or effects of drought, which may be associated with global warming.

A brief introduction to the basin and key system components is necessary at this point. From its sources in western Colorado, southwest Wyoming, and northeast Utah, the Colorado River travels 1,400 miles in a southwesterly direction to the Gulf of California. It drains an area of 242,000 square miles in the United States and 2,000 square miles in Mexico. Parts of the states of Colorado, Utah, Wyoming, Nevada, New Mexico, Arizona, and California lie within the drainage basin. The Colorado River Compact of 1922 divided the Basin into the Upper Basin and the Lower Basin for the purpose of apportioning beneficial consumptive use of the waters of the system. Lee Ferry, the division point between Upper and Lower Basins, is located near the Arizona-Utah border one mile below the mouth of the Paria River and

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seventeen miles below Glen Canyon Dam (Lake Powell). The Upper and Lower Colorado River Basins and major reservoirs are shown in Figure 2-1.

Upper Basin runoff is the unimpaired or virgin flow of the Colorado River at Lee Ferry, Arizona. This virgin flow is calculated from observed flow, with adjustments made for upstream use, out-of-basin diversions, and changes in reservoir storage. The flow at the Lee Ferry compact point is the sum of the Colorado River flow at the Lee Ferry gauging station and the flow of the Paria River which enters just upstream from Lee Ferry.

Measured virgin flow at Lee Ferry since 1896 has ranged between 5.0 and 24 million acre feet (maf) per year, with a long-term mean of about 15 maf (15.06). Of this amount, about 3.5 maf are currently being used in the Upper Basin and about 0.7 maf are exported out of the Upper Basin, largely to the Front Range communities of Colorado.

The first major storage reservoir on the Colorado River was Hoover Dam (Lake Mead), completed in 1936, which provides storage for assuring Lower Basin deliveries and for hydroelectric generation. Major water resource development in the Upper Basin began in the 1950's with the most important development being Glen Canyon Dam (Lake Powell). Completed in 1964, Glen Canyon Dam provided the Upper Basin with the storage needed to meet downstream obligations while increasing consumptive uses in the Upper Basin states.

Active storage capacities and average inflows to major reservoirs in the Colorado River Basin are shown in Table 2-1. Reservoirs having large amounts of storage capacity compared to their average annual inflows are termed *annual* reservoirs, while those with negligible storage capacity are termed *run of river*.

A study of severe, sustained drought affecting the Southwest involves establishing streamflow characteristics and the probabilities of drought events estimating the effects of storage systems on water availability at key points in the systems over time given streamflow characteristics during drought, and evaluating the relationships between available supplies and projected demands at key points during the period of analysis.

Details of drought hydrology are spelled out in the succeeding sections. The model which will be used for analysis is described below.
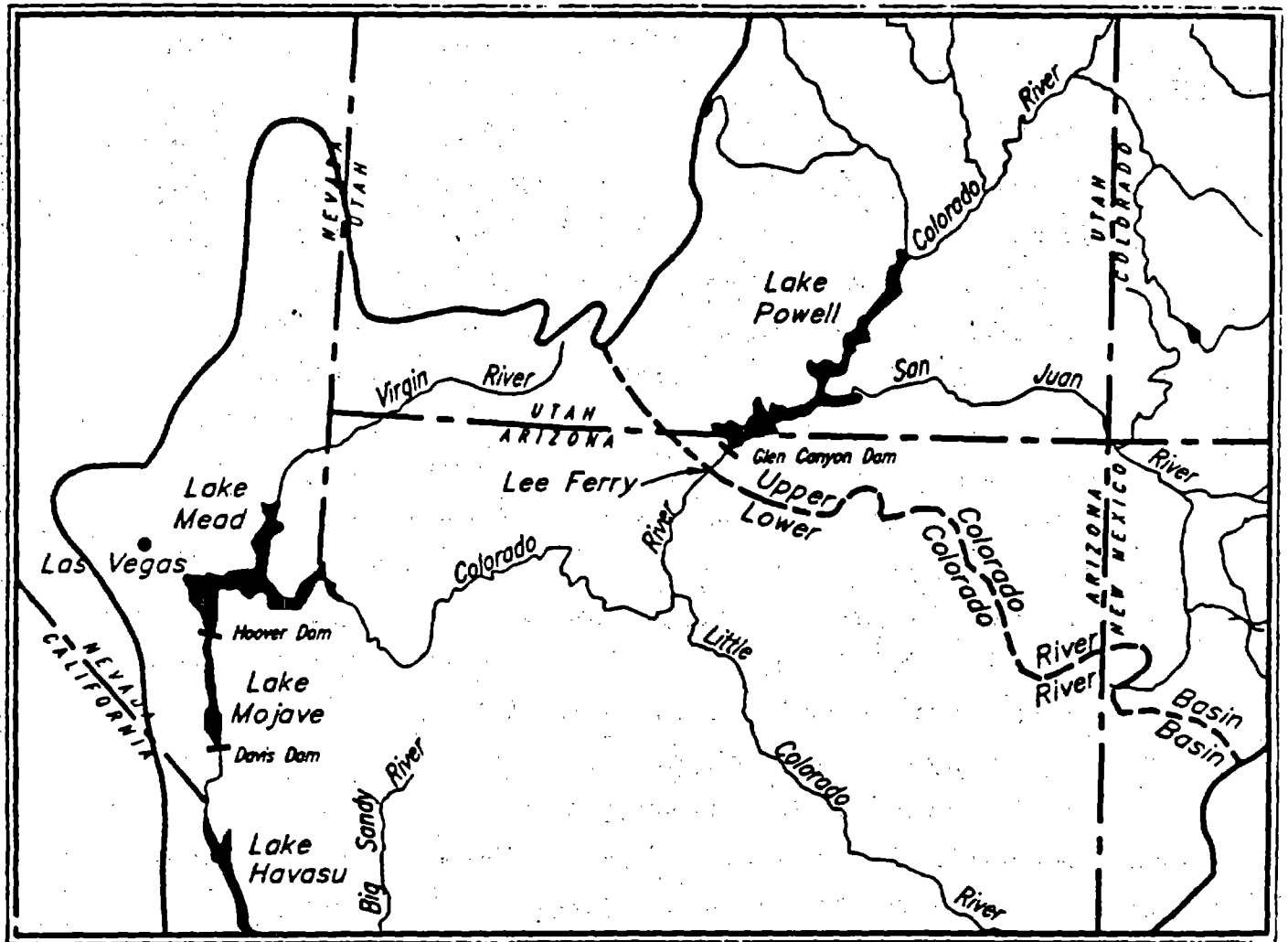
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Figure 2-1. The Upper and Lower Colorado River Basins and major reservoirs.

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Table 2-1. Major Storage Reservoirs in the Colorado River Basin.

Reservoir	Active Capacity MAF	Ann. Inflow MAF/Year	Reservoir Type
Fontenelle	0.345	1.3	Annual
Flaming Gorge	3.75	1.6	Cyclical
Blue Mesa	0.830	1.7	Annual
Morrow Point	0.117	1.7	Annual
Crystal	0.018	1.7	Run of River
Navajo	1.70	.900	Cyclical
Lake Powell	25.00	10.30	Cyclical
Lake Mead	25.88	10.10	Cyclical

Source: MWD Report 941, 1980

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The Analytical Model

Severe and sustained drought in the Colorado system will be buffered by the massive storage provided in the Colorado River Basin. For this reason, this drought analysis focuses on annual operation of the two major reservoirs in the Upper and Lower Basins, Lake Powell and Lake Mead, and the related effects on water availability relative to aggregate demand. Unimpaired measured streamflow at Lee Ferry, Arizona was taken to be the "base case" hydrology and was compared against reconstructed sequences of equal length from tree-ring data dating back to 1520.

The Colorado River Annual System Regulation Model (CRASR) was chosen for this study. It was substantially modified and rewritten by the authors to operate on a personal computer to reflect current operating regimes. The model is a tool for considering annual regulation of Lake Powell and Lake Mead. Seasonal operation is not so critical as in other river basins because of the large amount of storage capacity compared to annual runoff.

Total reservoir storage available is almost 60 maf. The combined live capacity of Lake Powell and Lake Mead is about 51 maf. Upper Basin runoff, the virgin flow of the Colorado River at Lee Ferry, has ranged between 5.0 and 24 maf, with a measured average flow of about 15 maf. This is shown in Figure 2-2.

The reservoir system model operates in accordance with the "Law of the River," and within certain physical limits. Maximum storage capacities of Lake Powell and Lake Mead are 25.00 maf and 25.88 maf, respectively (Table 2-1). Typical minimum storage capacities are 4.13 maf and 10.02 maf, respectively, and represent the minimum power pool below which power generation at the projects would be interrupted. Shortage releases are made from Lake Mead when storage falls below 10.62 maf.

The model responds to Section 602(a) of the Colorado River Basin Project Act, which allows for the storage in Lake Powell of water that is not required to be released (to Lake Mead) for Lower Basin use. Such storage is permitted to the extent that the Secretary of the Interior finds reasonably necessary in order to assure deliveries to the Lower Basin without impairment of future consumptive uses in the Upper Basin. Factors considered in determining this storage include Upper Basin demands, a minimum objective release of 8.23 maf per year from Lake Powell, the minimum power pool in the other Upper Basin
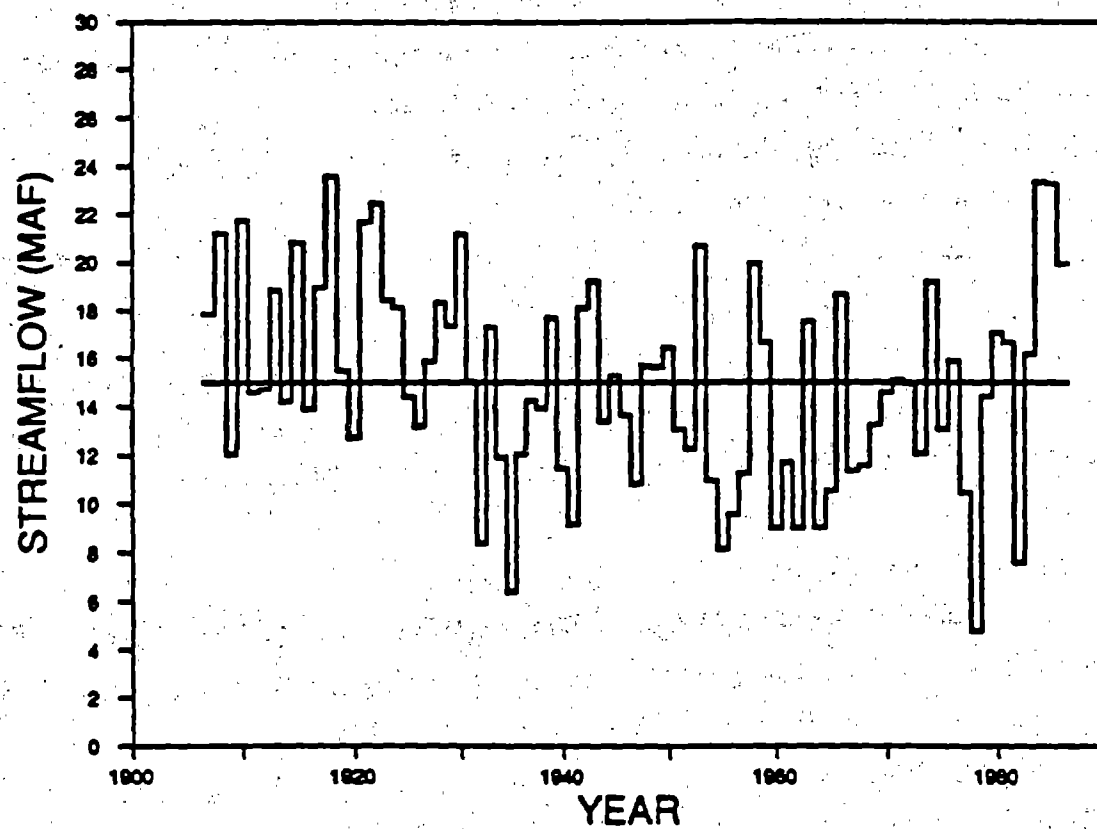
Figure 2-2. Colorado River Flow at Lee Ferry, Arizona

reservoirs, and natural flow at Lee Ferry for the 12-year critical period of 1953-1964.

As input, the CRASR model uses Upper and Lower Basin demands, initial reservoir storage, virgin flow or reconstructed sequences at Lee Ferry, Arizona, and certain operating constraints. A strict accounting is maintained of all quantities of water involved. Each acre-foot of unimpaired or virgin flow to Lake Powell is accounted for, as either an Upper Basin depletion (which includes reservoir evaporation), a storage change in Lake Powell or Lake Mead, or a Lake Mead outflow to meet water demands. Within the two reservoirs, flow continuity is maintained by a simple mass balance:

$$O = I \pm \Delta S$$

where O = outflow, I = inflow, and ΔS = change in reservoir storage. We think that the CRASR model, simplified though it is, captures the essential features of the operation of the Colorado River system. Details of this analysis are addressed in a later section.

Modeling Severe, Sustained Drought: Model Description

The Colorado River Annual System Regulation Model (CRASR) is concerned primarily with the annual regulation of Lake Powell and Lake Mead. Given projections of water demand, it is possible to use the model to determine the probabilities of water supply in future years in the Upper and Lower Basins in various circumstances of drought and streamflow.

The model draws on three principal categories of input data: unimpaired natural flows (which can be measured, reconstructed from tree-rings or synthesized using stochastic techniques) at Lee Ferry; a schedule of water demands or water depletions; and reservoir regulation criteria, which include physical and legal restrictions or constraints governing the regulation of the Colorado River System. Using these data, the program computes reservoir inflows, outflows, and storage contents, along with system water supply and power production, as shown schematically in Figure 2-3. These data document the water availability relative to selected demands.
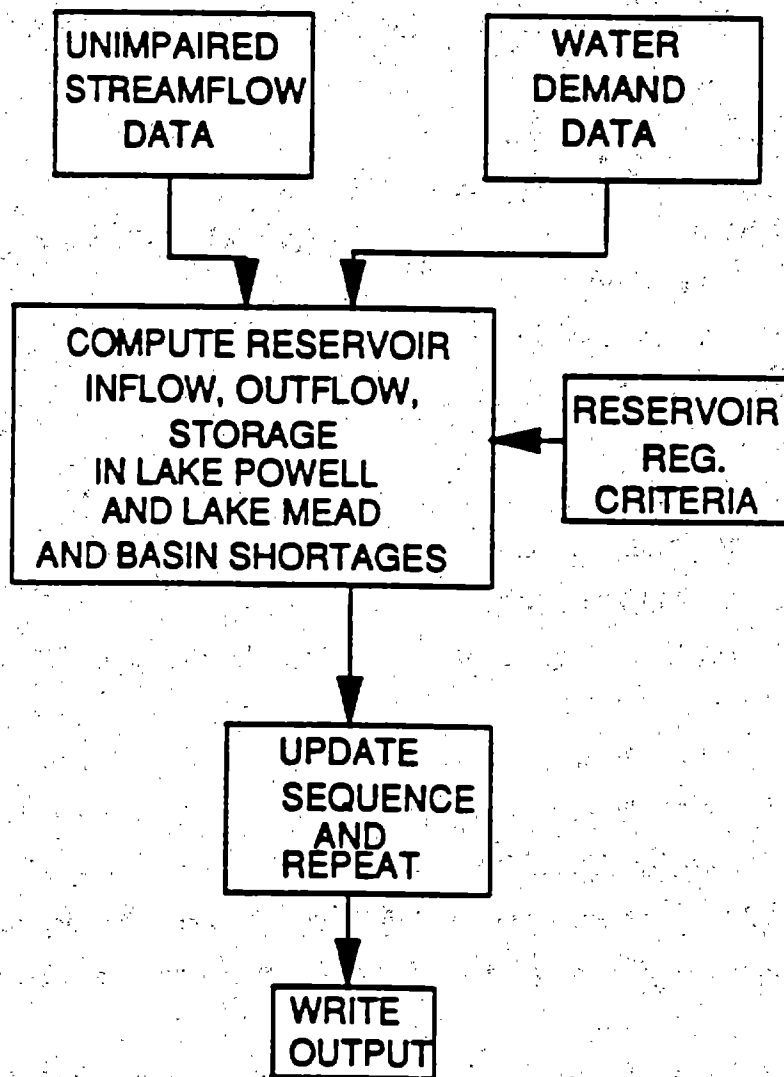
Figure 2-3. Schematic of CRASR Model.

If Lake Mead has sufficient empty storage capacity to regulate high inflows, and sufficient storage content above its minimum storage level to augment low inflows, reservoir releases will be made. However, when inflow exceeds outflow and there is insufficient storage space to store the difference, the excess inflow is added to the stipulated Hoover Dam release. When inflow is insufficient to meet the stipulated outflow and there is not enough water in storage to make up the difference, the Hoover Dam release is reduced.

Reservoir Regulation Criteria

The model operates the reservoir system in accordance with the Law of the River and within certain physical limits of the system. Those parts of the Law of the River of particular significance to the model are the following:

1. The Colorado River Compact
2. The Water Delivery Contracts
3. The California Seven-Party Agreement
4. The Mexican Water Treaty
5. The U.S. Supreme Court Decree in Arizona v. California
6. The Colorado River Basin Project Act
7. The Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs

Because this study uses a time interval of one year, it was not possible to simulate mandatory flood control evacuation required by the end of the calendar year. Flood control regulations for Lake Mead require that 5.35 maf of storage space be provided by January 1 of each year in Lake Mead or upstream reservoirs. It is assumed that normal seasonal regulation of the reservoirs will provide the additional control space that is required by January 1.

Minimum storage capacities for Lake Powell and Lake Mead used in the drought study were 4.13 maf and 10.02 maf, respectively. These represent the minimum power pool below which power generation at the projects would be interrupted. The Lake Mead storage values that triggered surplus and shortage releases were 22.92 maf and 10.62 maf, respectively.

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The joint operation of Lake Powell and Lake Mead responds to the following criteria in the Law of the River:

1. A Lake Powell minimum objective release of 8.2 maf per year.

2. Additional releases from Lake Powell to equalize end-of-year active storages in Lakes Powell and Mead if Lake Powell would otherwise contain more water in storage.

3. The minimum required water in storage in the Upper Basin reservoirs combined, called 602(a) storage under the Colorado River Basin Project Act of 1968. This storage refers to the quantity of water to be in storage in the Upper Basin so as to assure future deliveries to the Lower Basin without impairing annual consumptive use in the Upper Basin. This model used a 12-year critical period, from 1953 to 1964, to calculate the 602(a) storage requirements. It also considered minimum power pool in the other Upper Basin reservoirs and projected demand during the next 12 years for the Upper Basin depletions.

Allocation of Shortages

Articles II(3) and II(4) of the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs provide for releases from Lake Powell greater than 8.23 maf in order to achieve equalization between Lake Mead and Lake Powell. That is, an attempt is made to equalize the active storage between them. In addition, Section 602(a) of Public Law 90-537 provides for a minimum amount of storage in the Upper Basin which will assure Lower Basin deliveries without impairing Upper Basin consumptive uses. Part of the 602(a) storage calculation in this study assumed that during a critical drought period, annual shortages in the Upper Basin would be 6.12% of the total demand (USBR, 1985). This represents zero shortage on 2.1 maf of municipal and industrial (M&I) uses, and 10% shortage on 3.7 maf of irrigation uses.

For this analysis, a shortage condition was imposed when Lake Mead storage fell below 10.62 maf. Reservoir levels in Lake Mead and Lake Powell were not allowed to fall below minimum power pool levels. An examination of other possible shortage strategies was beyond the scope of this phase of the analysis.

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Simplifying Assumptions

Several simplifying assumptions are included in CRASR. Reservoir evaporation from Lake Powell and other Upper Basin reservoirs was considered to be constant from year to year, and was included in the Upper Basin depletions. Cyclical storage in reservoirs upstream from Lake Powell was ignored. No adjustments were made for siltation effects on Lake Powell and Lake Mead, or for bank storage.

The assumption of constant evaporation is reasonable under normal operating conditions because the evaporation would be buffered by the reservoir storage. However, under drought conditions, the evaporation would be reduced due to the smaller reservoir surface area. Therefore, the calculated shortages presented here are more severe than those which would be expected to occur.

Drought Characterization and Analysis

Dracup, Lee, and Paulson (1980b) identified four factors to be considered in characterizing drought: the nature of the water deficit (hydrologic, agricultural, or meteorological); the basic time unit of the data; the threshold level; and the selection of a regionalization or standardization approach. Each of these is discussed in the following pages relative to the type of drought envisioned for this study, that is, a severe, sustained drought.

Nature of the Deficit

Drought analysis over a large river basin such as the Colorado may be usefully approached from the perspective of meteorological drought. Streamflow is perhaps the best hydrologic variable at this scale, since it integrates a variety of processes over a watershed, such as runoff, soil moisture, and evapotranspiration. Changes in climate are thus reflected as changes in streamflow volumes over a specified time period.

Traditionally, water resources design, such as reservoir sizing, has been predicated on an assumption about the statistical parameters of historic streamflow series called *stationarity*, in which the parameters which characterize historical streamflow series do not change with time. This is not to say that climate is stationary, since changing climate has been accounted for in water resource system designs by considering the variance of streamflow (σ^2) about its mean $(\overline{Q})$. Stationarity assumes, however, that future variations in climate, as expressed in

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streamflows, will be similar to those observed in the past. Typically in the western United States, the record consists of a period of streamflow measurement on the order of 60 to 80 years. At Lee Ferry, Arizona, Colorado River streamflow records date back to 1906. This 80-plus-year period contrasts to over 450 years (from 1520) of reconstructed streamflow records at Lee Ferry based on tree-ring studies, which offer a far richer record of variability than the measured record. Climate changes affected by anthropogenic activities may alter hydrologic cycles, as dramatized in recent years by increasing concern about effects of growing atmospheric concentrations of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and tropospheric ozone (O_3), key contributors to the "greenhouse effect."

The increase in CO_2 and other gases is well established scientifically (AAAS, 1990). A study of ice core data also shows a strong correlation of temperature rise with increased levels of CO_2. The magnitude, regional and temporal variations, and impacts of global warming are, however, uncertain (U.S. EPA, 1988). There is also controversy in the scientific community over whether global warming may have already begun (Hansen and Lebedeff, 1987; Hanson et al., 1989).

Impacts of global warming on the hydrologic cycle would constitute invalidation of the stationarity assumption. Dracup and Kendall (1991) showed that relatively modest warming could have a significant effect on the occurrence and severity of droughts. A five-percent downward shift in the mean annual flow of four rivers central to California water storage and supply systems would produce a 20 percent increase in the occurrence of droughts as classified by the California Department of Water Resources (Kendall and Dracup, 1988). Other CO_2-induced climate change studies in the western United States show that the impacts would be severe and widespread (AAAS, 1990).

The magnitude of the change in these statistical parameters is unknown. And while our studies considered a shift only in the mean ($\overline{Q}$), there is no reason to believe that a shift would not also occur in the variance (σ^2), or skew (γ). Rather than perform a sensitivity analysis with these parameters, and create a number of what-if scenarios, a decision was made to utilize the streamflow reconstructions provided by tree-ring analyses from the basin's recent past.

A comparison of some reconstructed sequences using hydrologic streamflow records of equal length are shown in Table 2-2. What is most striking is the smaller mean annual

Table 2-2. Comparison of Reconstructed and Measured Flows at Lee Ferry, Arizona.

Tree Ring 1520-1599	Tree Ring 1600-1679	Tree Ring 1680-1759	Tree Ring 1760-1839	Measured 1906-1985
13.35 maf	13.43 maf	13.78 maf	12.97 maf	15.06 maf

flow for the reconstructed sequences, which ranges from 12.97 to 13.78 maf, compared to the 1906-1985 record of 15.06 maf. Stochastic flows generated from an autoregressive model of order 1 (AR(1)) were also considered in the drought study. It will be shown that hydrologic sequences provided by tree-ring reconstructions were the most appropriate choice for this level of analysis.

Basic Time Interval of the Data

Drought analyses are typically considered on a monthly or annual time scale. For this analysis, a time scale of one-year intervals was chosen, consistent with the resolution provided by tree-ring reconstructions.
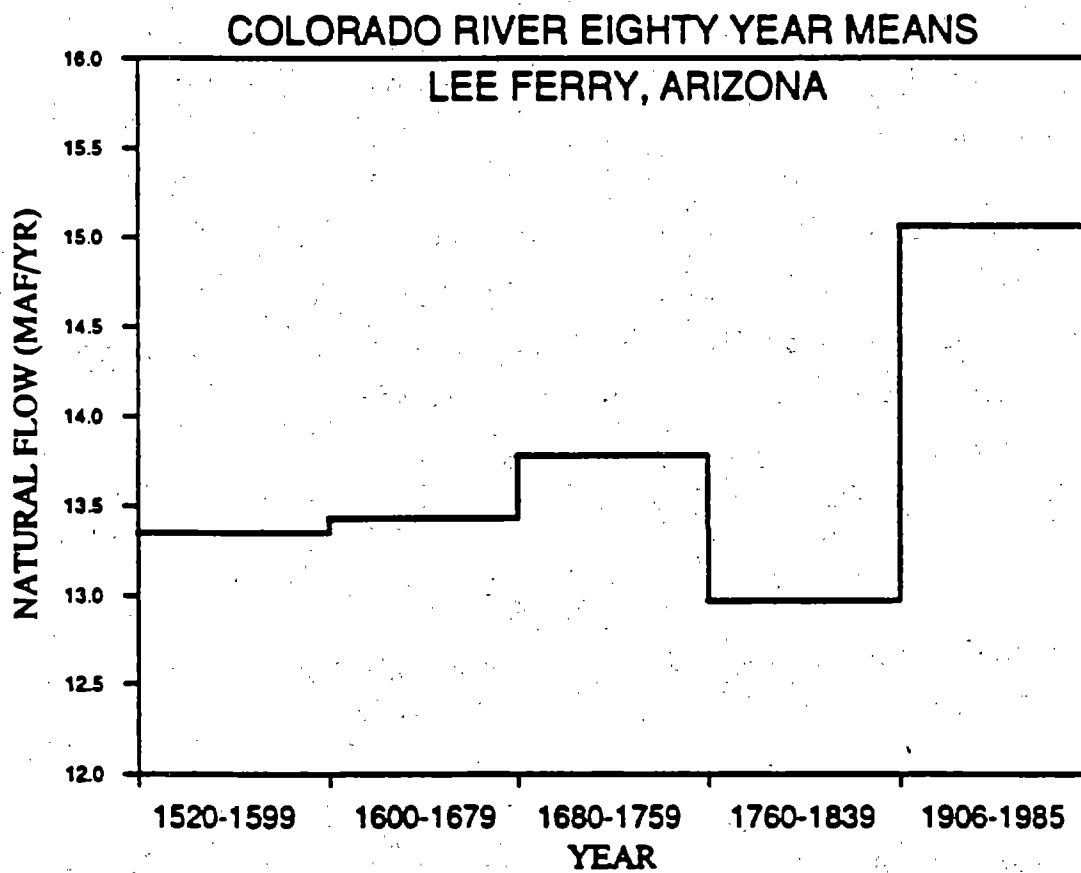
Threshold Level

Threshold levels in drought analyses are typically taken to be a streamflow's mean or median. Other appropriate thresholds may include average annual demand. For this analysis the threshold level was taken to be the mean annual measured unimpaired flow at Lee Ferry, important because comparisons using this threshold level will be made with reconstructed annual unimpaired flows at Lee Ferry from tree-ring data.

Drought Parameters in the Colorado

A discussion of the Hurst phenomenon, which is the analysis of persistence in hydrology, is found in the Appendix. One reason suggested for this persistence behavior is that the process which governs streamflow is non-stationary in its mean. Incorporation of tree-rings into this type of analysis gives a measure of support to this idea. An anthropogenically induced climate change would also exacerbate this process. Evidence of a nonstationarity in the mean is shown in Figure 2-4.

Analyses performed by a panel on water and climate for the National Academy of Sciences (Wallis, 1977) argued against a stationarity-independent or short memory process giving rise to the Colorado River flows. Furthermore, the panel estimated the long-term mean for flows at the Lee Ferry compact point to be 13.5 maf.

Drawing on the previous discussions, a drought may be characterized as any year or consecutive series of years during which average annual streamflow is continuously below

COLORADO RIVER EIGHTY YEAR MEANS
LEE FERRY, ARIZONA

Figure 2-4. Colorado River at Lee Ferry - Nonstationary Mean

some specified threshold level, which is typically taken to be the long-term mean (Yevjevich, 1967; Dracup et al., 1980a).

A drought event is considered to be composed of three defining attributes: duration, D; severity, which is the cumulative deficit, S; and magnitude, which is the average water deficit, M; such that $S = M \times D$. Since the parameters are interrelated, any two are necessary and sufficient to completely define a single drought event (Dracup et al., 1980b). Duration and severity are the most strongly correlated parameters, and may be considered to be the two primary parameters dependent on streamflow values. Magnitude is a secondary parameter; duration and magnitude are weakly correlated.

Based on this definition of drought we may write the severity of a multiple-year drought as

$$S_d = Y_1^d + Y_2^d + ... + Y_d^d$$

where

> d = drought duration (years)
>
> Y_n^d = deficit in year n of a d year drought (maf)
>
> Assuming that the deficits are independent and identically distributed, we may write

the expected value and the variance of drought severity as

$$E(S_d) = E(Y_1^d + Y_2^d + ... Y_d^d) = d \, E(Y_i^d)$$

and

$$VAR(S_d) = E(d \cdot VAR(Y_i^d)) + VAR(d \cdot E(Y_i^d))$$

What is interesting to note about these last two equations is that their relationships hold without any assumptions when viewed from a computational standpoint. As will be shown later, the expected value of streamflow deficit is a function of drought duration d.

As shown in Table 2-3, twenty hydrologic droughts have occurred over the period of record from 1906 through 1985. Of these, four had a severity of over 15 maf, with a duration

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Table 2-3.   Historical Hydrologic Droughts on the Colorado River at Lee Ferry, Arizona 1906-1985.

Drought No.	Duration (Years)	Starting Year	Severity (maf)	Magnitude (maf/year)
1	1	1909	2.954	2.954
2	2	1911	0.665	0.333
3	1	1914	0.769	0.769
4	1	1916	1.103	1.103
5	1	1920	2.290	2.290
6	2	1925	2.432	1.216
7	1	1932	6.609	6.609
8	5	1934	16.520	3.304
9	2	1940	9.382	4.692
10	1	1944	1.617	1.617
11	2	1946	5.506	2.753
12	2	1951	4.678	2.339
13	4	1954	20.092	5.023
14	3	1960	15.267	5.089
15	2	1964	10.422	5.211
16	4	1967	9.176	2.294
17	2	1972	2.971	1.486
18	1	1974	1.945	1.945
19	3	1977	15.351	5.117
20	1	1982	7.410	7.410

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ranging from 3 to 5 years. It is apparent that a severe and sustained drought in the Colorado River Basin, given system storage, is not necessarily produced by a single continuous drought event, but may arise from a series of events separated by one or two years. For the period of record, a series of droughts that define the "critical period hydrology" for the Colorado River began in 1954 and continued through 1971.

Two sets of 80-year sequences from tree-ring reconstructed streamflows at Lee Ferry which exhibited different types of *severe* droughts were chosen for the purpose of comparison. The periods selected are 1520-1599 (Figure 2-5) and 1600-1679 (Figure 2-6). These periods display different types of droughts with regard to their number, duration, and severity. The sequence from 1520-99 displays a series of droughts, four of which contribute collectively toward a severe and sustained drought condition from 1573 through 1597 (Table 2-4). The 1600-79 sequence displays the most sustained drought, a 15-year drought beginning in 1659 (Table 2-5).

Maintaining the same threshold level of 15 maf (the long term mean from 1906-85) for all sequences, fifteen drought events were identified for both tree-ring reconstructed streamflow records. Drought characteristics differ significantly. The period from 1520-99 exhibits four droughts beginning in 1573 and extending through 1597. These are shown in Table 2-4. Conversely, the period from 1600-79 displays a single severe drought of a 15 years' duration, as shown in Table 2-5.

Generation of Severe, Sustained Droughts:
Flow Comparisons by Data Source

Generated Stochastic Flows for Lee Ferry

Part of this investigation centered on whether or not severe sustained droughts on the Colorado River could be better represented stochastically with an autoregressive zero-order (AR(1)) or low-order memory model. Examination of tree-ring reconstructed flows, particularly in relation to their mean, would argue against this. That is, nonstationarity behavior is observed. As noted earlier, the conventional method has been to use index-sequential hydrologic sequences. As a point of comparison, however, a simulation was made using both approaches.
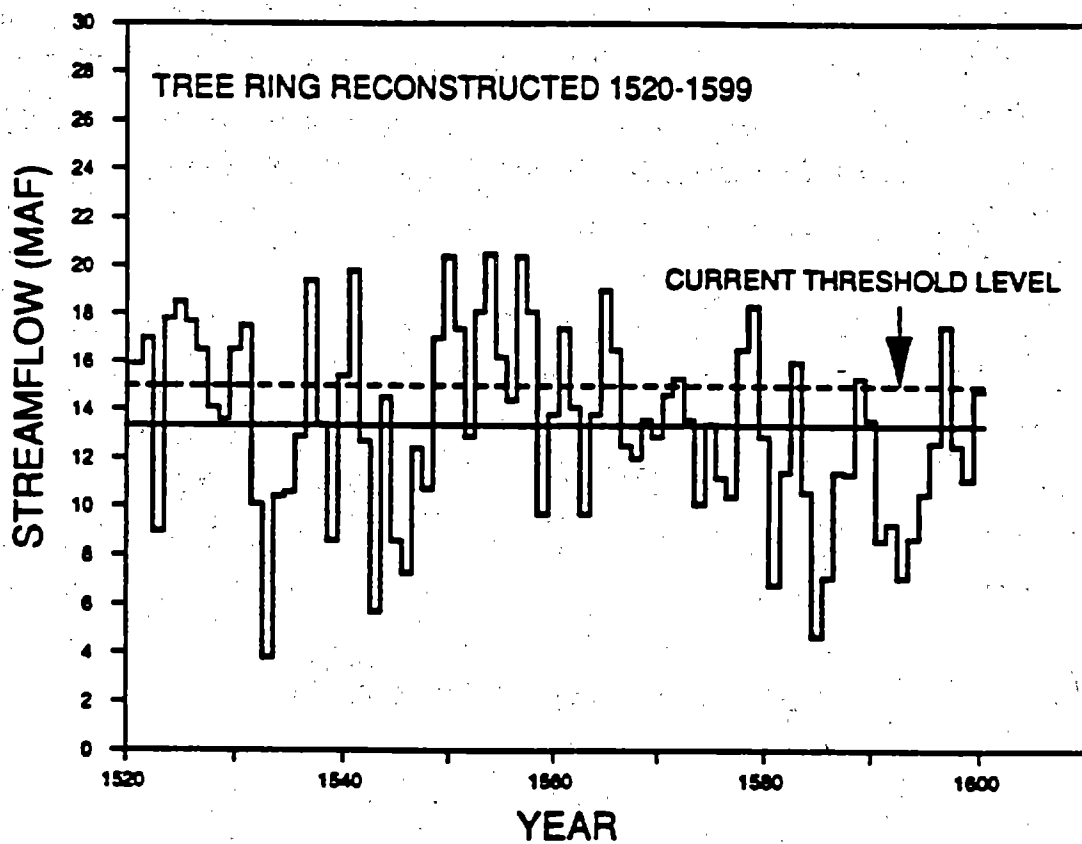
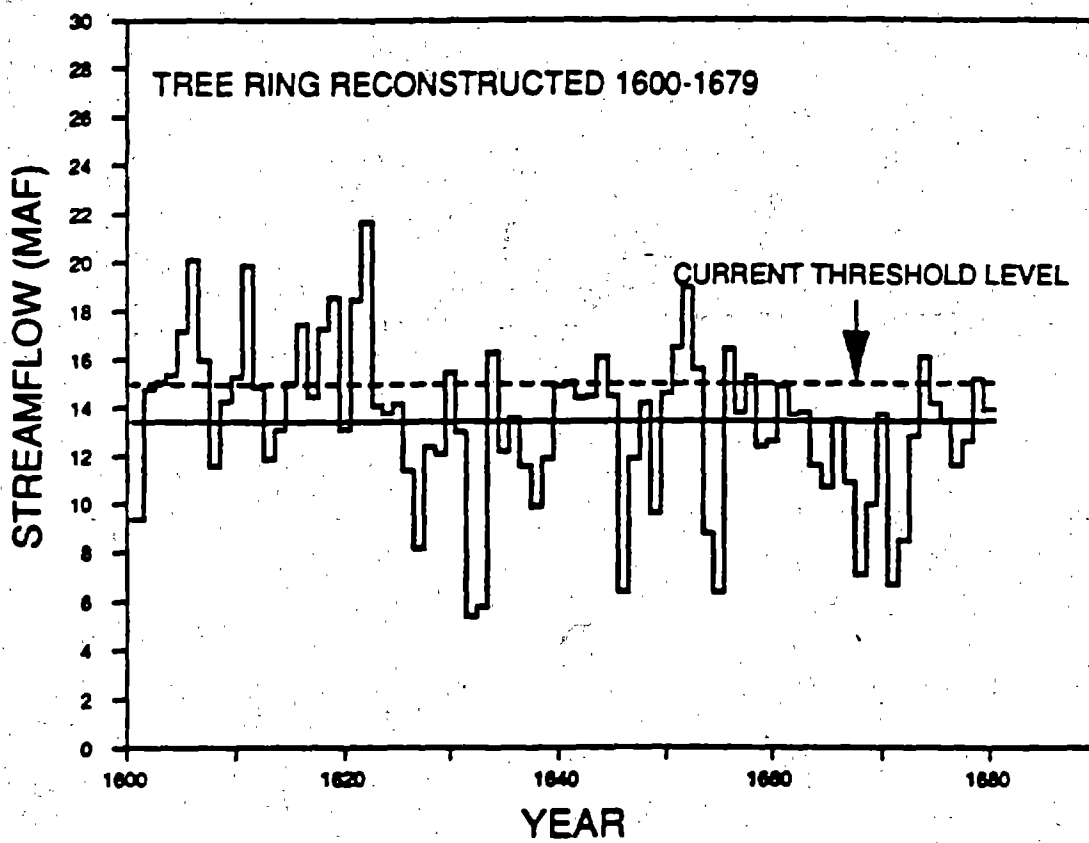Figure 2-5. Streamflow Sequence at Lee Ferry, 1520-1599.

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Figure 2-6. Streamflow Sequence at Lee Ferry, 1600-1679.

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Table 2-4. Tree Ring Reconstructed Hydrologic Droughts on the Colorado River at Lee Ferry, Arizona 1920-1599.

Drought No.	Duration (Years)	Starting Year	Severity (maf)	Magnitude (maf/year)
1	1	1523	6.000	6.000
2	2	1528	4.600	2.300
3	5	1532	27.20	5.440
4	2	1538	8.000	4.000
5	7	1542	33.10	4.729
6	1	1552	2.100	2.100
7	1	1556	0.600	0.600
8	2	1559	6.500	3.250
9	3	1562	7.400	2.467
10	5	1567	9.400	1.880
11	5	1573	16.30	3.260
12	3	1580	13.90	4.633
13	5	1584	29.90	5.980
14	7	1590	34.60	4.943
15	3	1598	6.600	2.200

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Table 2-5. Tree Ring Reconstructed Hydrologic Droughts on the Colorado River at Lee Ferry, Arizona 1600-1679.

Drought No.	Duration (Years)	Starting Year	Severity (maf)	Magnitude (maf/year)
1	2	1601	5.800	2.900
2	2	1608	4.200	2.050
3	3	1612	5.100	1.700
4	1	1617	0.500	0.500
5	1	1620	1.900	1.900
6	7	1623	18.80	2.686
7	3	1631	20.80	6.933
8	6	1635	15.90	2.650
9	2	1642	1.100	0.550
10	6	1645	18.80	3.133
11	2	1654	14.80	7.400
12	1	1657	1.200	1.200
13	15	1659	52.10	3.773
14	4	1675	8.100	2.025
15	1	1680	1.100	1.100

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The AR(1) model is written as

$$X_{t+1} = \mu_x + \rho_1(x)(X_t - \mu_x) + e_t\,\sigma_x\,(1 - \rho_1^2(x))^{\frac{1}{2}}$$

where:

X$_t$=ln(Q$_t$) are transformed annual streamflows

e$_t$ is independent zero mean unit variance white noise

μ_x is the mean of the log transformed flows

σ_x is the standard deviation of the transformed flows

ρ_1 is the serial correlation of the transformed flows

The synthetic streamflows generated at Lee Ferry include uncertainty in the estimated parameters of the annual streamflow model. Two thousand sequences were generated, utilizing a software package, SPIGOT (Grygier and Stedinger, 1987 and 1988). This model was originally written for use on a VAX system. Results presented in this study, however, represent a version of SPIGOT which was compiled for personal computer use by the authors. With the exception of a random number generator routine, however, the PC version is completely analogous to the mainframe version. (A new version of SPIGOT specifically for the personal computer is expected to be released in 1990 (Grygier, 1990).)

SPIGOT generated streamflows in a two-step process. Consider the following form for the AR(1) model:

$$X_{t+1} = \alpha + \beta\,X_t + V_t$$

where:

V$_t$ are independent zero-mean normal random variables

$$\beta = 1$$

$$\alpha = \mu(1-\beta)$$

Zellner (1971) showed that the standard deviation, σ, of generated streamflows X$_t$ has an inverse chi distribution if the information used to determine alpha and beta comes only from the historical record. A given σ, α and β have a multivariate normal distribution. Thus, N streamflow sequences are generated by first generating N complete sets of parameters $\hat{\sigma}$, $\hat{\alpha}$, and $\hat{\beta}$. Each set of parameters is then used to generate one streamflow sequence.

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Comparison Between Historical and Generated Statistics

A comparison between historical and generated statistics for Lee Ferry, Arizona is shown in Table 2-6. Monthly flows were summed to annual values to serve as input to the regulation model. The standard deviation of the means of the annual flow sequences was 0.874 maf, while the standard deviation of the sequence standard deviations was 0.511 maf.

Index Sequential Hydrologic Sequences

The ability of the AR(1) model to reproduce historical statistics can be thought of as a verification procedure. However, its ability to reproduce drought events as or more severe than those seen in the historical record must be demonstrated through some type of simulation. While the sequent-peak procedure has been used (Stedinger and Taylor, 1982b, Kendall and Dracup, 1991), synthetic and historical hydrologic sequences were run through CRASR. The historical sequences were created with a procedure known as the *index-sequential* method. In order to develop probability estimates of water supply, many agencies in California and the United States use the index-sequential method to create a set of realistically probable streamflows. Each sequence differs from the next only by the fact that the first streamflow year is incremented by one. For example, in hydrologic sequence 1, the first historic streamflow is assumed to occur in the first demand year of a study. In sequence 2, the second historic streamflow occurs in the first demand year, with the first historic streamflow being wrapped to the bottom of the deck, so to speak. Consequently, there are as many sequences as there are years of hydrologic data. This procedure is currently practiced by the California Department of Water Resources (DWR, Division of Planning), the U.S. Bureau of Reclamation (CRSS model), the Los Angeles Department of Water and Power (Coufel, 1989), and the Metropolitan Water District of Southern California (MWD, 1989). While stochastic flow studies have been carried out by some of these agencies (Lane et al., 1975; Arora, 1984; LADWP, 1987), the use of the index-sequential method appears to be the procedure of choice.

Engineers have traditionally relied on a concept known as critical-period planning when making simulation or design studies. Drawbacks in this approach have been documented by several authors, including Loucks et al. (1981), Lettenmaier et al. (1984), and

Table 2-6. Comparison of Historic Streamflow and AR(1) Model Statistics (Thousands of Acre-Feet).

Month	Hist.	$\bar{Q}$ AR(1)	Hist.	σ AR(1)	Hist.	AR(1)
Annual	15063	15132	4082.3	4158.5	0.160	0.161
Jan	334.9	364.5	60.49	96.78	0.546	0.557
Feb	374.8	407.8	92.57	126.6	0.256	0.545
Mar	628.3	674.2	209.2	239.4	0.235	0.446
Apr	1211.2	1276.7	496.8	524.3	0.387	0.370
May	3096.7	3241.9	1108.0	1067.4	0.547	0.413
Jun	4153.5	4643.8	1529.1	2023.0	0.605	0.549
Jul	2188.8	2477.0	912.4	1285.9	0.815	0.804
Aug	1064.0	1136.4	420.6	444.8	0.722	0.592
Sep	638.4	677.5	331.4	315.0	0.622	0.443
Oct	560.4	611.6	279.2	313.5	0.502	0.419
Nov	452.7	493.7	122.8	166.5	0.710	0.511
Dec	359.3	390.3	70.78	108.1	0.705	0.559

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Vogel and Stedinger (1988). The use of wrapped hydrologic sequences can be viewed as an extension of critical-period planning. The objective is to compute probability of reservoir storage or supply deficits at, for example, a particular level or year of demand. The ensemble of wrapped sequences essentially represents a cycling of the critical period relative to a prespecified demand year and level. A fundamental drawback with this approach is that the critical period observed in this historic record of the past is the worst that ever occurs in any of the wrapped sequences, unless the beginning and end of the historic record are low flow periods, and appear as periods of scarcity in the early years of sequence-wrapping.

Wrapped hydrologic sequences of the historic record are not additions to the random process expressed in years of record, even though they are so treated when probability curves are developed. The correlation structure of the measured data set is preserved, an important factor in multi-site models where modelers may want to preserve cross-correlations. In the wrapped sequence method, persistence is preserved but flows are constrained in space and time to those observed in the one (historical) realization of a random process.

A simulation was performed utilizing measured unimpaired hydrology at Lee Ferry (1906-1985) with the AR(1) model and the index-sequential method. Average Lake Mead storage levels are shown in Figure 2-7. Likewise, average Lake Powell levels are shown in Figure 2-8. As can be seen, there is essentially no difference between the two approaches from an average perspective. This is not unexpected, considering that the AR(1) model reproduces mean annual flows very well. On the other hand, the AR(1) model does a better job at the tail of the probability distributions that can be developed as shown in Figure 2-9 for Lake Powell, and Figure 2-10 for Lake Mead. Which method should be applied when studying severe and sustained drought? It is easily seen that the AR(1) model developed with current measured hydrology would not be able to produce droughts as severe as those observed from tree-ring reconstructions (due to the nonstationary, lower mean). Furthermore, an AR(1) model developed from statistics based on those reconstructions would add uncertainty to uncertainty, given the observed bias mentioned below. For these reasons then, the decision was made to use the reconstructed data, along with the index-sequential procedure for the generation of pseudo-likely sequences. We consider it to be the best procedure for comparing the effects of a severe, sustained drought, albeit imperfect.
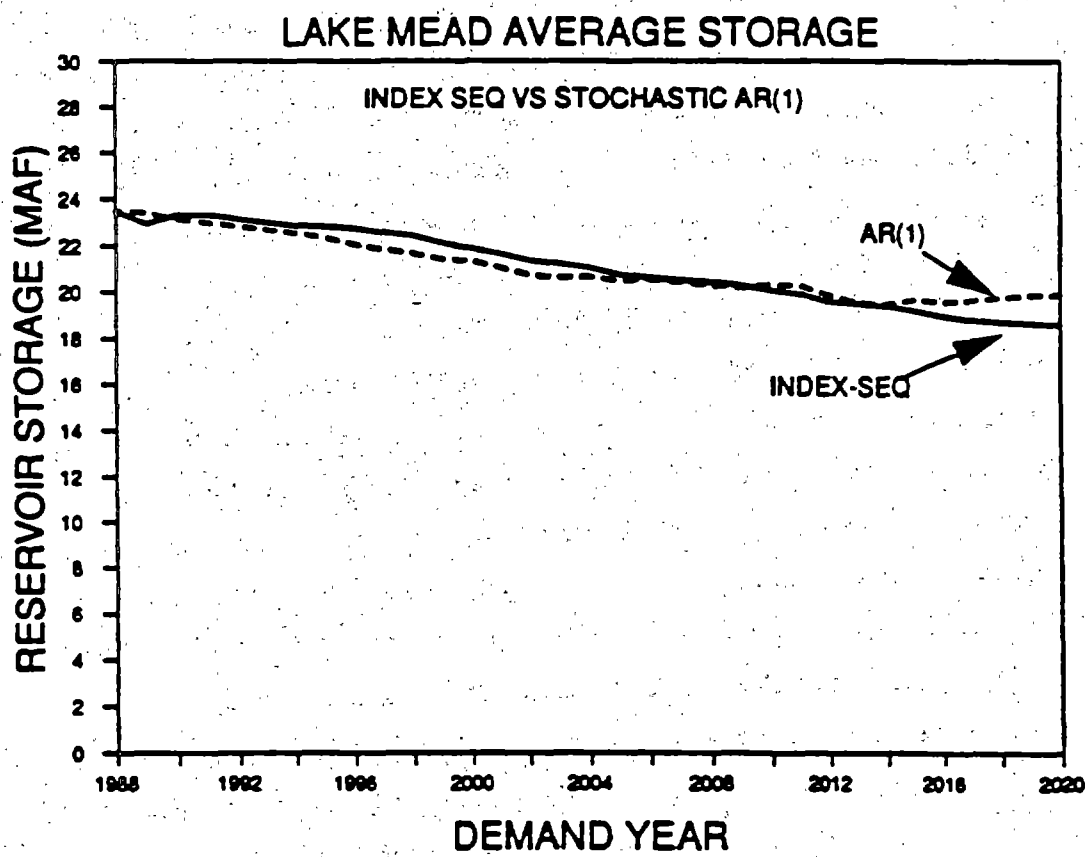
LAKE MEAD AVERAGE STORAGE

INDEX SEQ VS STOCHASTIC AR(1)

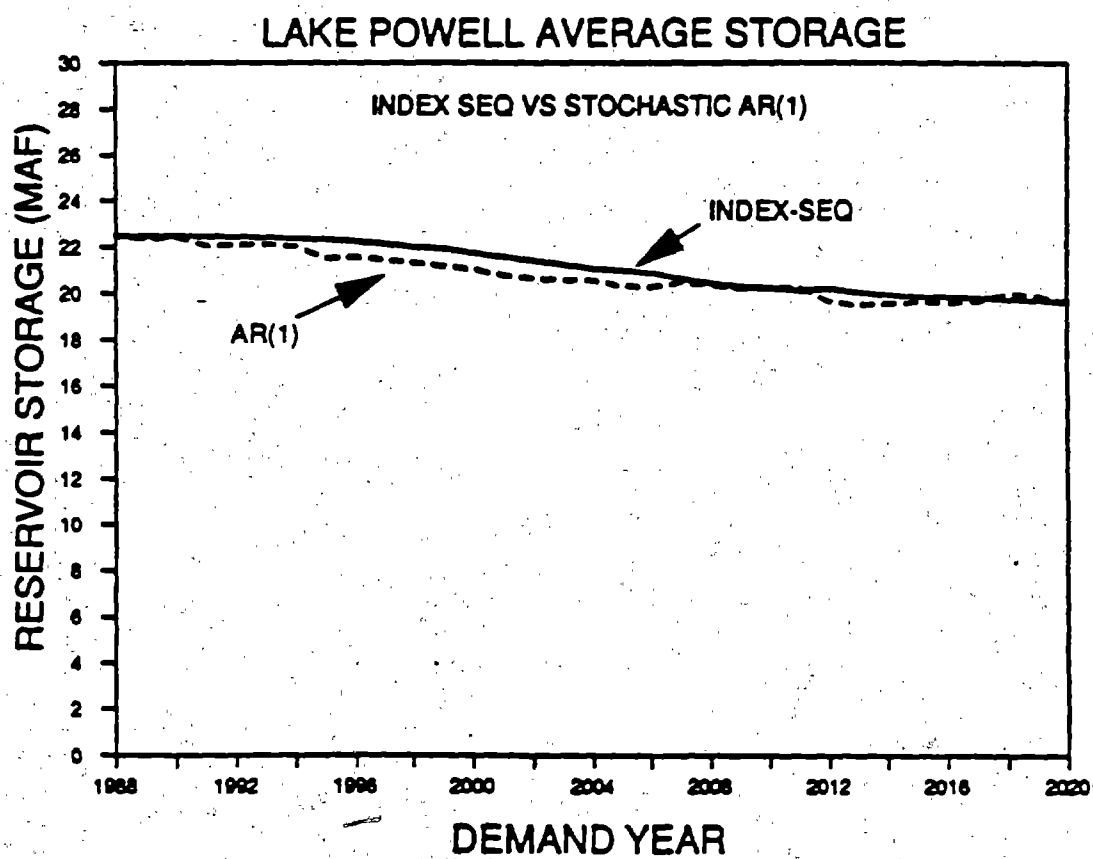Figure 2-7. Comparison of Lake Mead Average Storage.

Figure 2-8. Comparison of Lake Powell Average Storage.
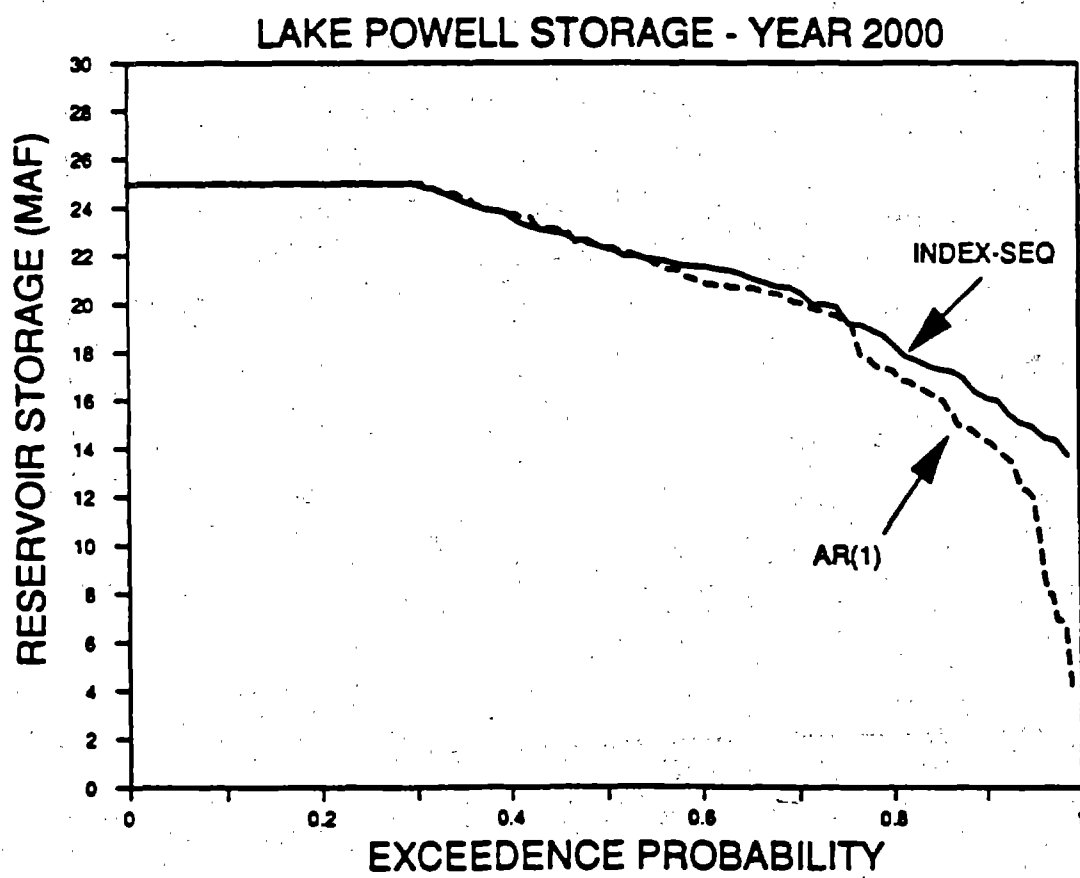
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Figure 2-9. Comparison of Lake Powell CDF - Year 2000.
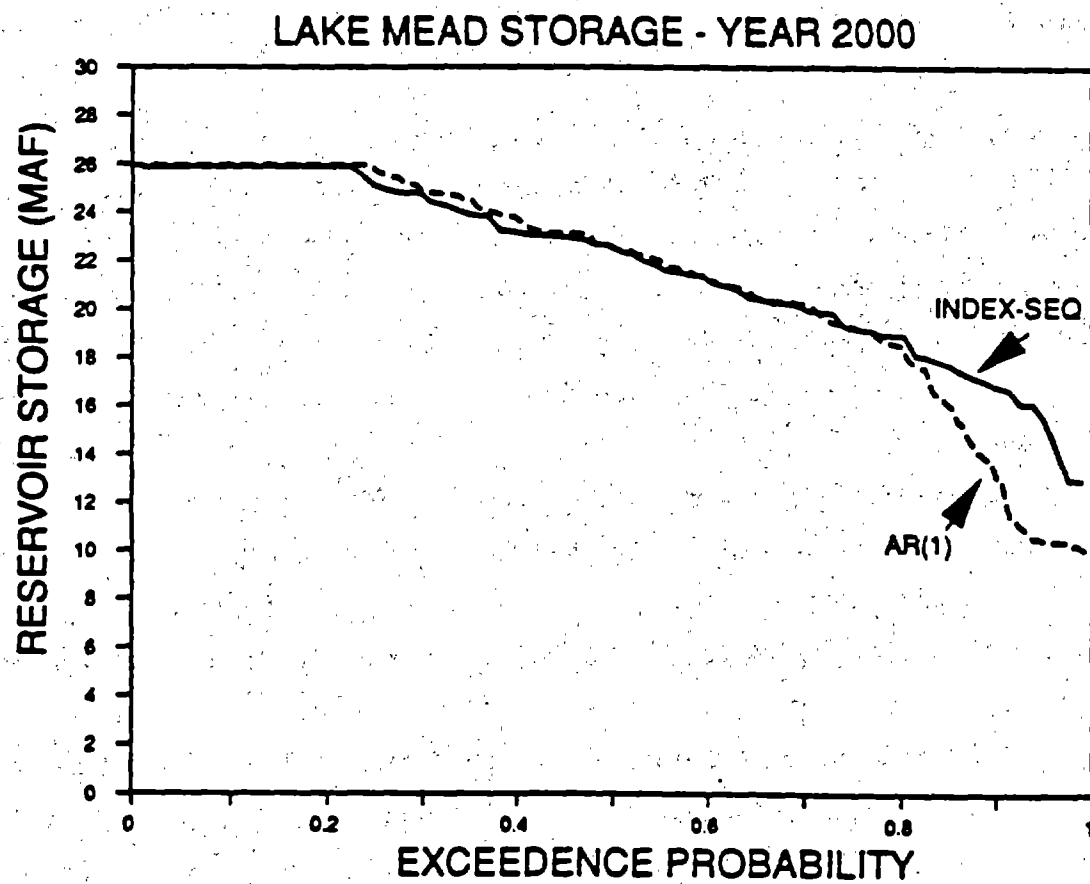
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Figure 2-10. Comparison of Lake Mead CDF - Year 2000.

One could argue for the use of a fractional Gaussian noise model which preserves long-term persistence. However, as noted by Stedinger and Taylor (1982a), these models suffer from serious parameter estimation error, in which case one is better off using an AR(1) model which accounts for uncertainty in its parameters. But that model assumes stationary parameters such as the long term mean. Rather than get caught up in the dilemma of which model to use, it is consistent with the objectives of this analysis to simply use existing historical (reconstructed) streamflow data. Additionally, meaningful conclusions can be drawn from averaged simulation results. And as demonstrated previously, the index-sequential procedure and the stochastic AR(1) model produce essentially indistinguishable results at an average level.

Simulation Comparisons Between Tree Ring and Measured Flows

Matalas and Fiering (1977) noted that a bias exists in geochronological records such as tree-rings when used to estimate streamflows. Long-term mean estimates are reasonable, but tree-ring indices are more normally distributed and more highly correlated than streamflow. However, it has never been determined whether these differences in statistical properties are significant enough to offset the utility of reconstructed flows in water resource systems analyses.

As a point of comparison, simulations were performed for the period of record 1906-1961 where there were overlapping streamflow estimates for Lee Ferry from tree-ring reconstructions and streamflow measurements (see Figure 2-11). (The tree-ring reconstructed flows were actually calibrated against the 1922-1988 record; streamflow measurements from 1906-1921 were not included for calibration purposes because of concern for measurement reliability.) The differences are reflected in Figure 2-12 for Lake Powell storage and in Figure 2-13 for Lake Mead. Maximum lake level differences are on the order of about 1 million acre-feet over the 32-year simulation period, with the tree-ring reconstructions providing a lower estimate of storage than the measured flows. The mean annual measured flows were 15.41 maf, while the mean annual reconstructed flows were 15.04 maf. The difference in lake levels between the two simulations produces a small shortage in the Lower Basin as shown in Figure 2-14. Upper Basin average shortages are shown in Figure 2-15.
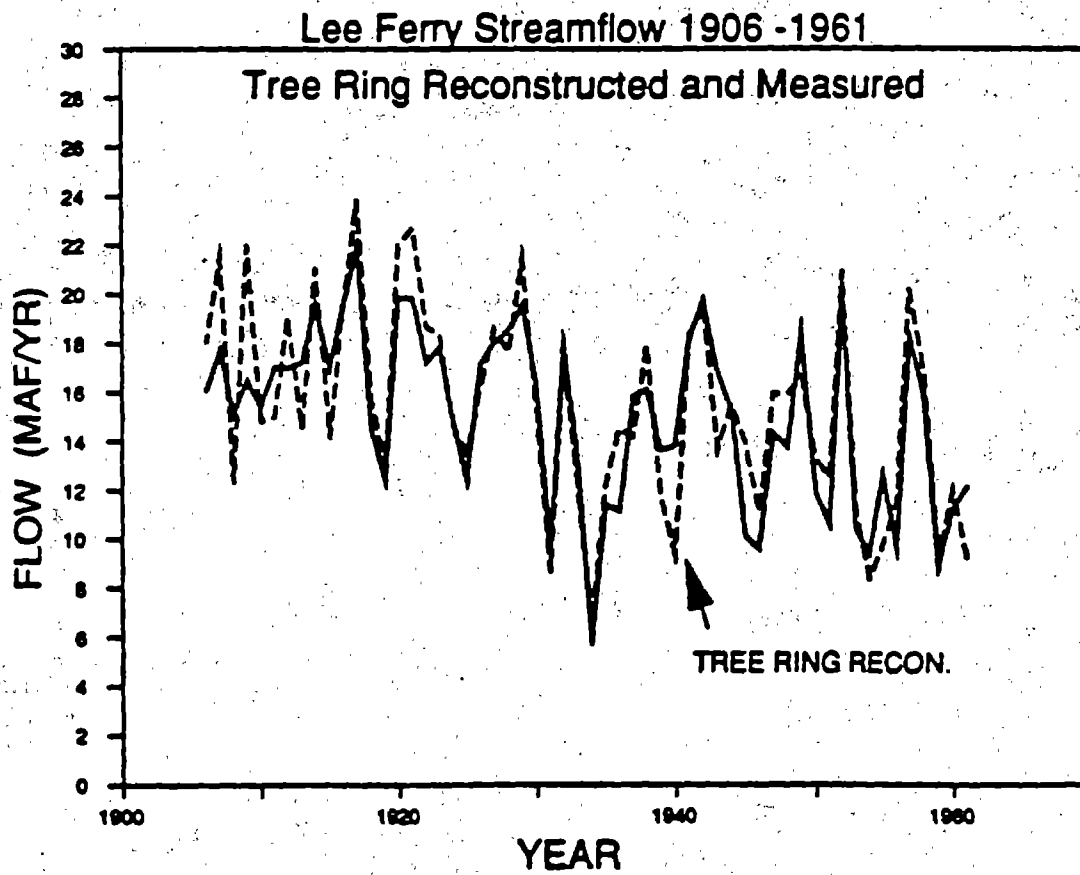
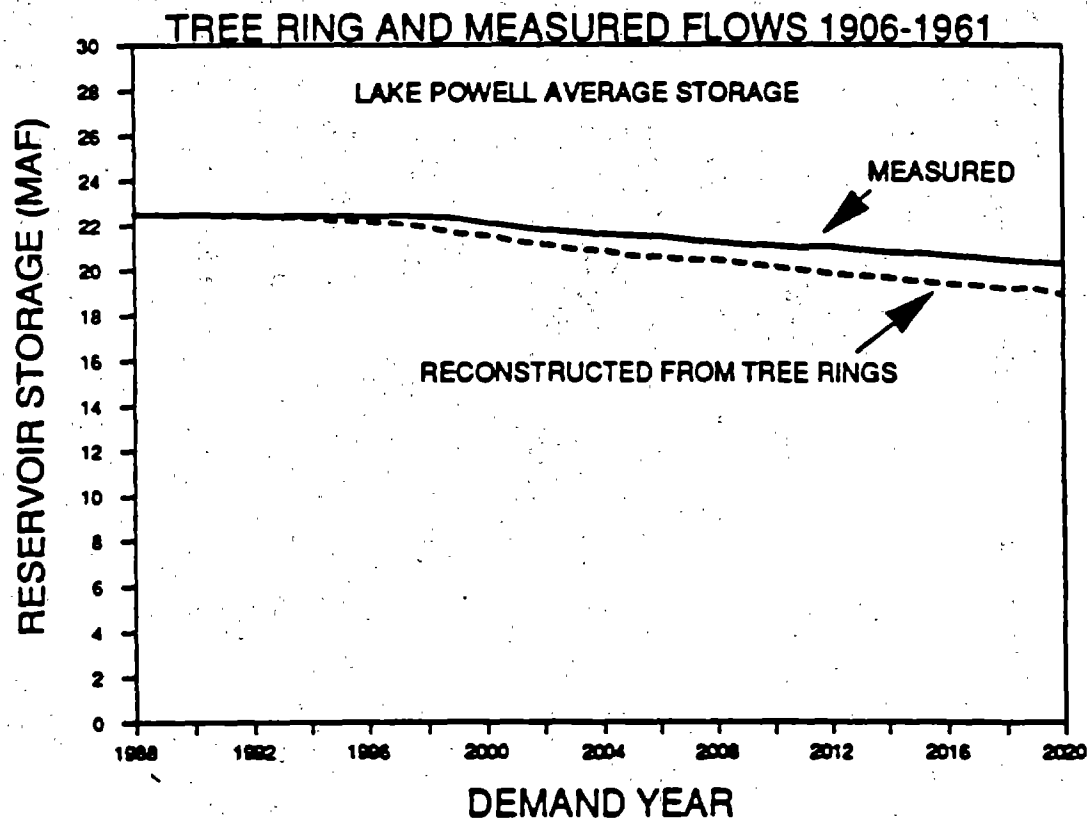Figure 2-11. A Comparison Between Tree-Ring and Measured Flows.

TREE RING AND MEASURED FLOWS 1906-1961

LAKE POWELL AVERAGE STORAGE

MEASURED

RECONSTRUCTED FROM TREE RINGS

RESERVOIR STORAGE (MAF)

DEMAND YEAR

Figure 2-12. Lake Powell Average Storage Comparison.

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TREE RING AND MEASURED FLOWS 1906-1961

LAKE MEAD AVERAGE STORAGE

MEASURED

RECONSTRUCTED FROM TREE RINGS

(Y-axis: RESERVOIR STORAGE (MAF), 0 to 30)

(X-axis: DEMAND YEAR, 1988 to 2020)
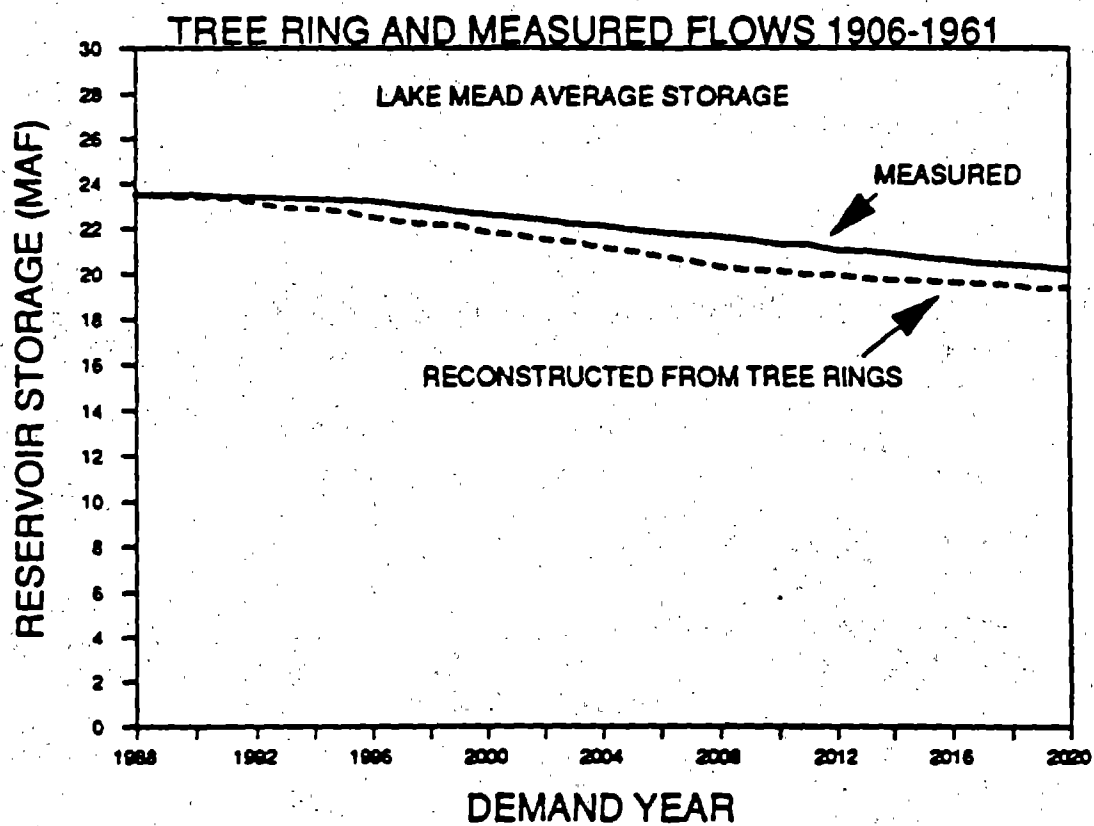
Figure 2-13. Lake Mead Average Storage Comparison.

TREE RING AND MEASURED FLOWS 1906-1961

LOWER BASIN AVERAGE SHORTAGE

RECONSTRUCTED FROM TREE RINGS

MEASURED

SHORTAGE (MAF)

DEMAND YEAR
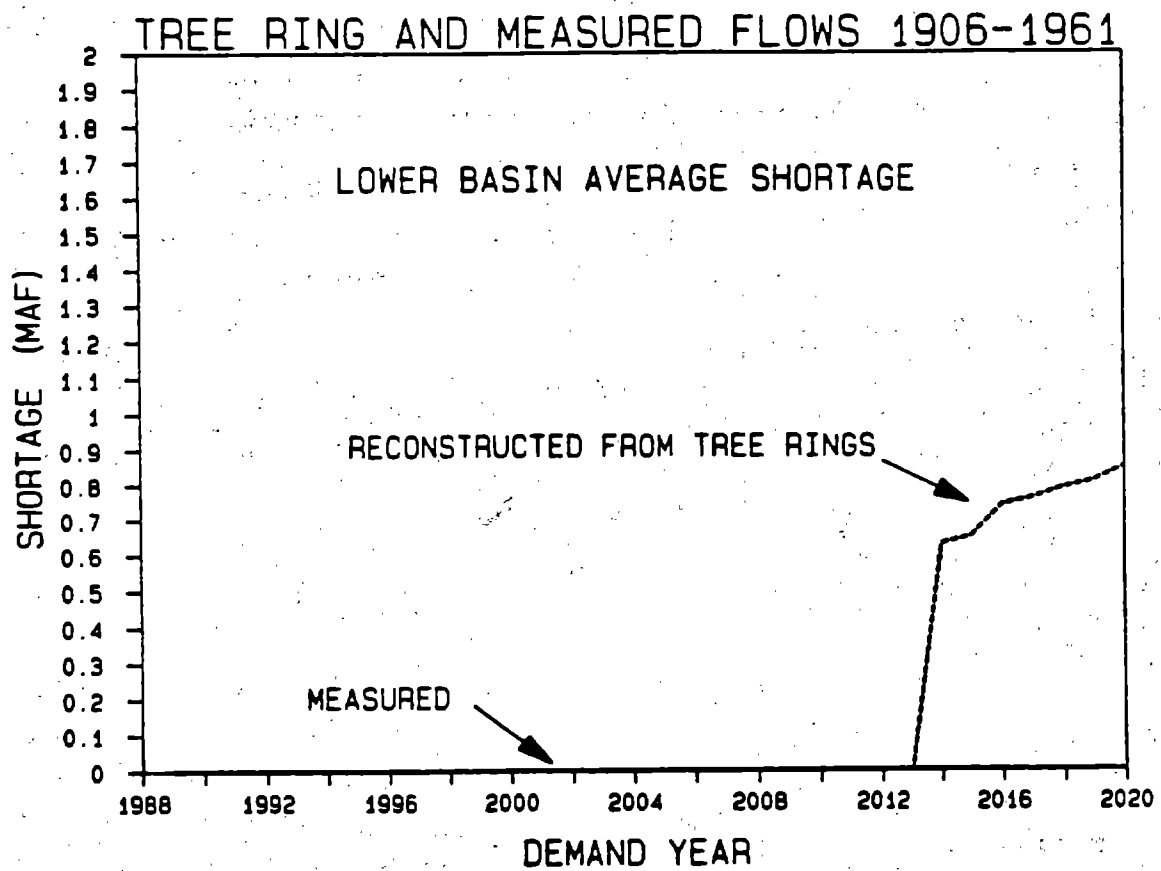
Figure 2-14. Lower Basin Average Shortage Comparison.

TREE RING AND MEASURED FLOWS 1906-1961

UPPER BASIN AVERAGE SHORTAGE

RECONSTRUCTED FROM TREE RINGS

MEASURED

SHORTAGE (MAF)

DEMAND YEAR
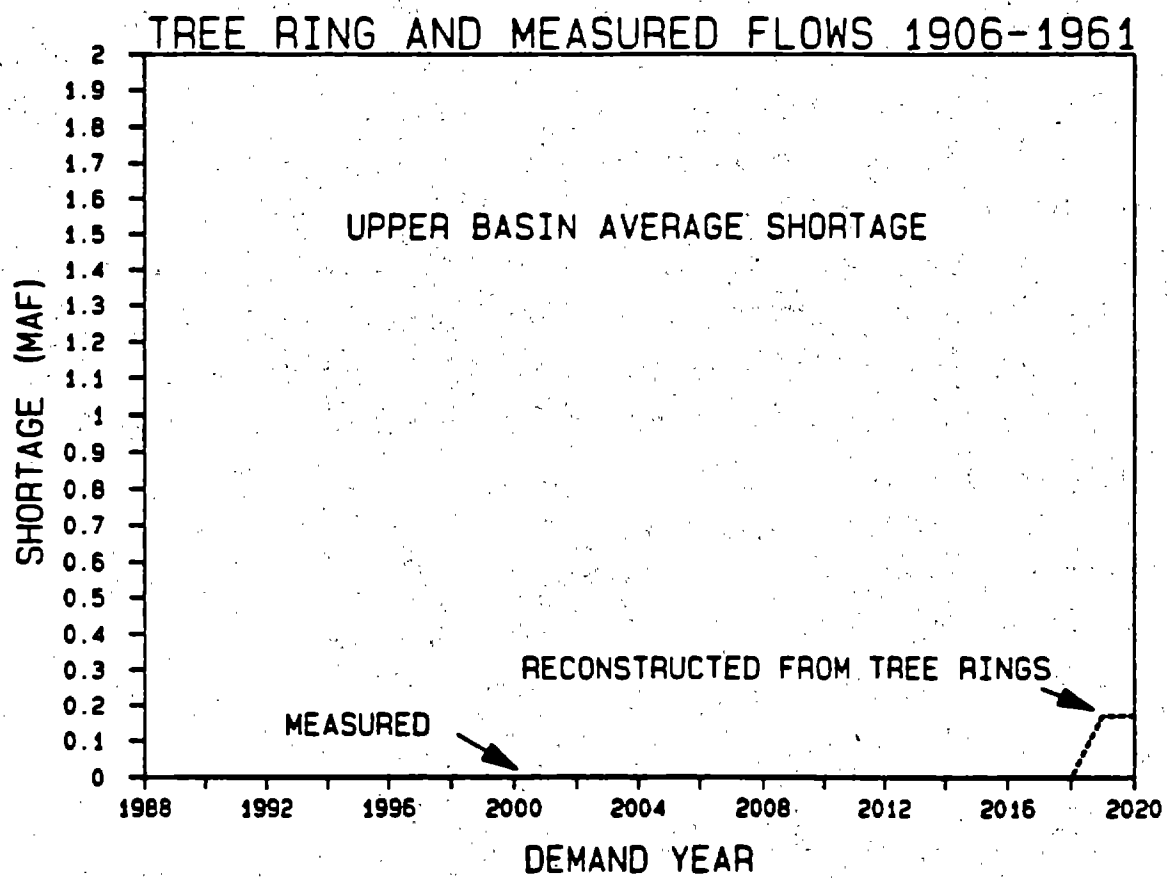
Figure 2-15. Upper Basin Average Shortage Comparison.

Demand Assumptions

System regulation studies to determine future water supplies are performed over a series of years to accommodate growing demands. For this study, a demand period from 1989 to 2020, or 32 years, was simulated to accommodate the rather large drought periods observed in the tree-ring reconstructed hydrologic sequences. Demand data is taken from data used by the Bureau of Reclamation as the base case for its Colorado River System Simulation (CRSS) model.

The model output is directly related to the hydrologic sequence input. For water system design purposes, streamflow is recognized as a random process, of which the historic hydrologic record is one expression.

The hydrologic sequences comprise what can be taken to be year-to-year water supply. Coupled with this are year-to-year water demands. When demands exceed supplies, additional yield is provided from water stored in reservoirs. Water losses due to evaporation or seepage from the conveyance system can be regarded as an additional demand.

The Upper and Lower Basin demand schedule used in the analysis is shown in Tables 2-7 and 2-8. These data are consistent with those in the USBR's model of the Colorado River (CRSS).

Lower Basin demands include all uses from Lake Mead and downstream. The demands include those for California, Arizona, Nevada, and Mexico, as well as net losses below Lake Mead.

Operating the Model

Comparison of Severe, Sustained Drought Simulations

Simulations were made for the hydrologic period 1906-1985 (the base case), 1520-1599, and 1600-1679. Each simulation produced results from 80 index-sequential hydrologic sequences, and included reservoir storages, releases, and imposed shortages in the Upper and Lower Basins. These results were ranked using a Weibull plotting position, in order to form empirical cumulative distribution functions (CDF). Average storages, releases, and shortages were also computed. The simulations were based on one interpretation of the Law of the

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Table 2-7.   Upper Colorado River Basin Water Demands (maf).

Water Year	Normal Demands (incl. Mexico and losses)
1988-89	3.540 acre feet
1989-90	3.550
1990-91	4.040
1991-92	4.050
1992-93	4.060
1993-94	4.070
1994-95	4.080
1995-96	4.090
1996-97	4.200
1997-98	4.310
1998-99	4.410
1999-2000	4.520
2000-01	4.630
2001-02	4.640
2002-03	4.660
2003-04	4.680
2004-05	4.700
2005-06	4.720
2006-07	4.740
2007-08	4.760
2008-09	4.780
2009-10	4.800
2010-11	4.830
2011-12	4.840
2012-13	4.860
2013-14	4.870
2014-15	4.890
2015-16	4.900
2016-17	4.910
2017-18	4.930
2018-19	4.940
2019-20	4.960

Source: USBR 1985

Table 2-8.   Normal Lower Colorado River Basin Water Demands (maf).

Water Year	Moderate Demand
1988-89	9.370
1989-90	9.460
1990-91	9.480
1991-92	9.490
1992-93	9.490
1993-94	9.500
1994-95	9.500
1995-96	9.510
1996-97	9.510
1997-98	9.520
1998-99	9.530
1999-2000	9.540
2000-01	9.550
2001-02	9.550
2002-03	9.550
2003-04	9.550
2004-05	9.550
2005-06	9.550
2006-07	9.550
2007-08	9.550
2008-09	9.550
2009-10	9.550
2010-11	9.550
2011-12	9.550
2012-13	9.550
2013-14	9.560
2014-15	9.560
2015-16	9.560
2016-17	9.570
2017-18	9.570
2018-19	9.570
2019-20	9.580

Source: USBR 1985

River, and the 602(a) storage requirement. The CRASR model operates on an annual level and includes several simplifying assumptions listed earlier. For this type of analysis, the absolute value of a particular parameter such as reservoir storage is not as significant as the difference between two simulations.

Lake Powell

This chapter displays results derived from simulating 80 index-sequential sequences for each of three 80-year hydrologic periods on the Colorado River: 1906-1985 (the base-case years of record), 1520-1599, and 1600-1679. Each simulation included streamflow at Lee Ferry and reservoir storages, and releases, given water demands as specified in Table 2-7 and 2-8 for periods beginning in water year 1988-89.

Results in terms of reservoir storage levels in Lake Powell (for Upper Basin) and Lake Mead (for Lower Basin), based on interpretation of the Law of the River and the 602(a) storage requirement, were ranked according to probability of occurrence (using a Weibull plotting position) in order to provide empirical cumulative distribution functions (CDF). In other words, the probability of an occurrence of a specific storage level was determined by plotting storages for each of the 80 years of the sequentially-indexed hydrologic records, and determining probabilities for each storage level.

Average storages and releases were also computed and plotted. The specific parameter selected for display is the probability that storages at specific levels would be exceeded for each of the specific streamflow/storage/demand sequences for the year displayed.

Exceedence probabilities developed for Lake Powell showed that a repeat of a hydrologic period like that of 1520-1599 or 1600-1679 would be significant. At the 90% exceedence level,[1] the difference between the base case period (1906-1985) and 1520-1599 is about 11 maf for the year 2000. Lake Powell is at minimum power pool at 85% exceedence, as shown in Figure 2-16. Minimum power pool exceedence decreases to 80% and 75% by the year 2010 and 2020 respectively as shown in Figures 2-17 and Figure 2-18.

A comparison of the two drought scenarios shows that they have similar probability curves with maximum differences at the lower exceedence levels. While both sequences

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[1] i.e., a 90% probability the reservoir storage will be equal to or greater than the indicated amount.
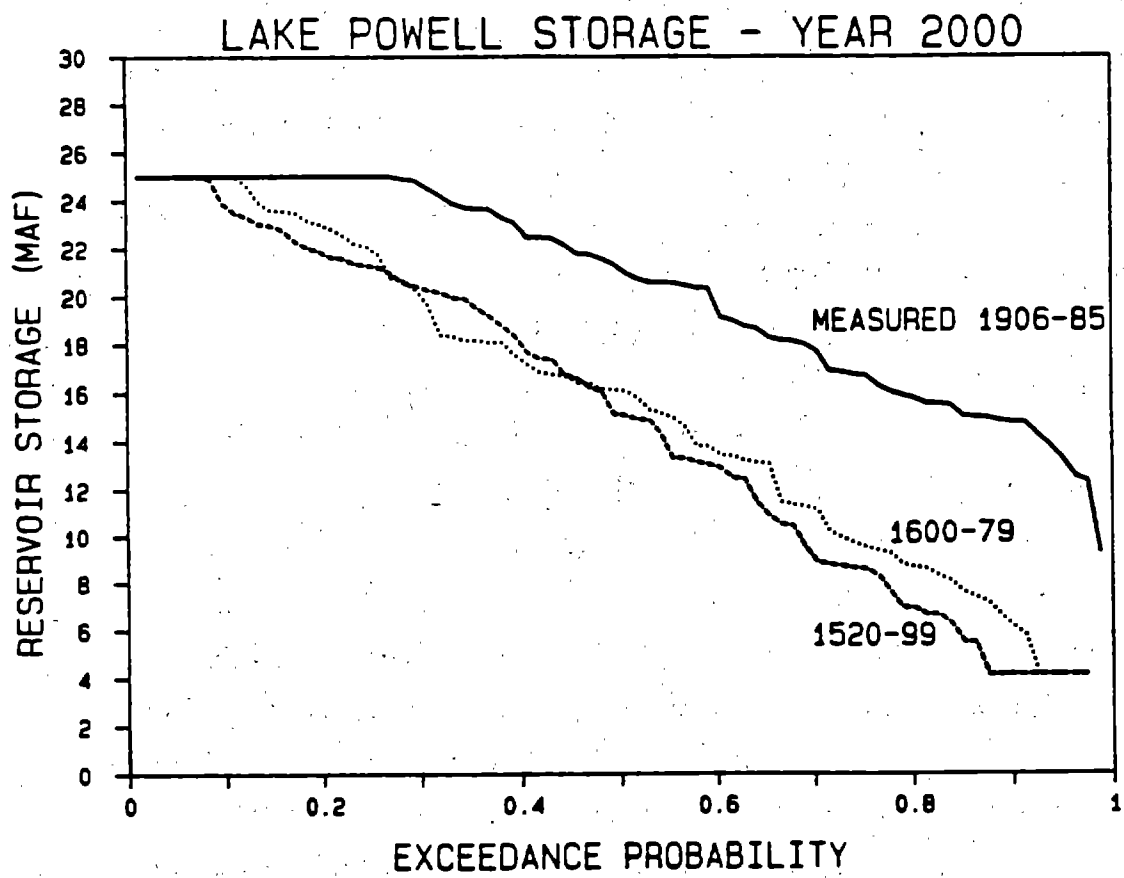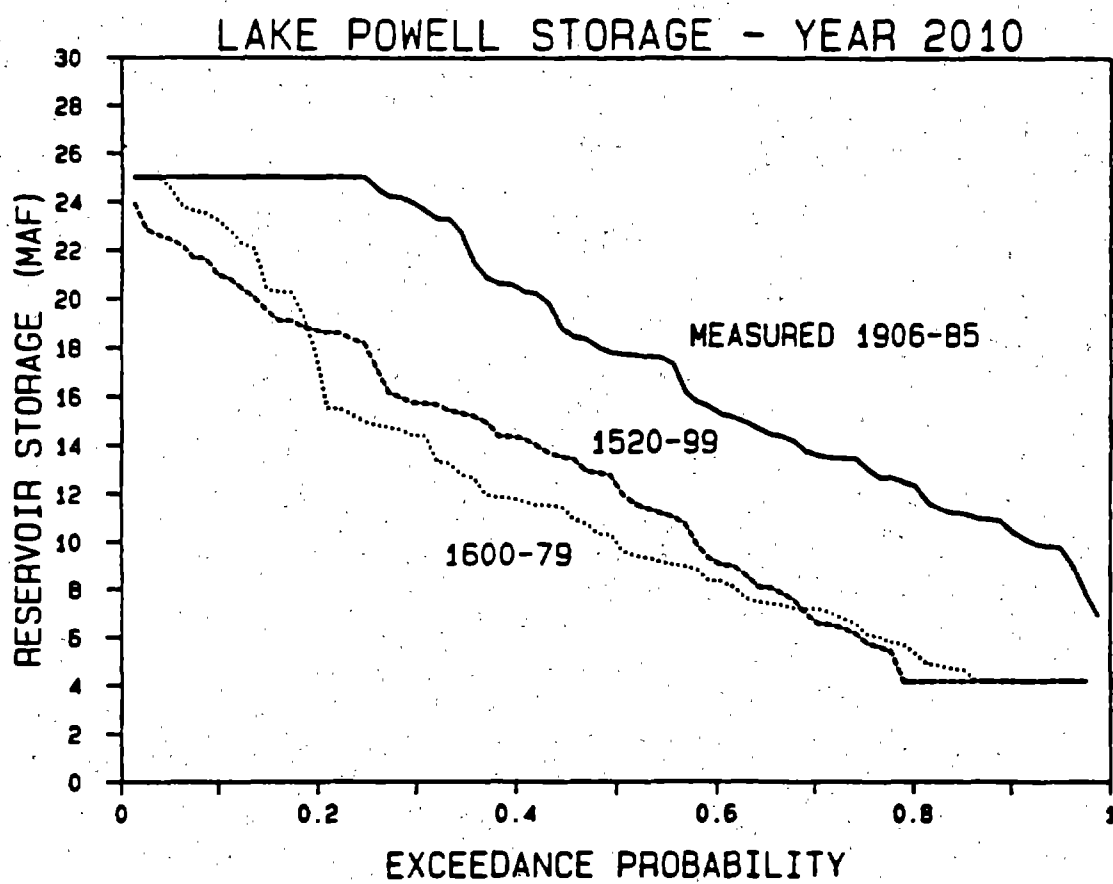
LAKE POWELL STORAGE - YEAR 2000

MEASURED 1906-85

1600-79

1520-99

RESERVOIR STORAGE (MAF)

EXCEEDANCE PROBABILITY

Figure 2-16. Lake Powell Storage CDF - Year 2000.

Figure 2-17. Lake Powell Storage CDF - Year 2010.

LAKE POWELL STORAGE - YEAR 2020

MEASURED 1906-85

1520-99
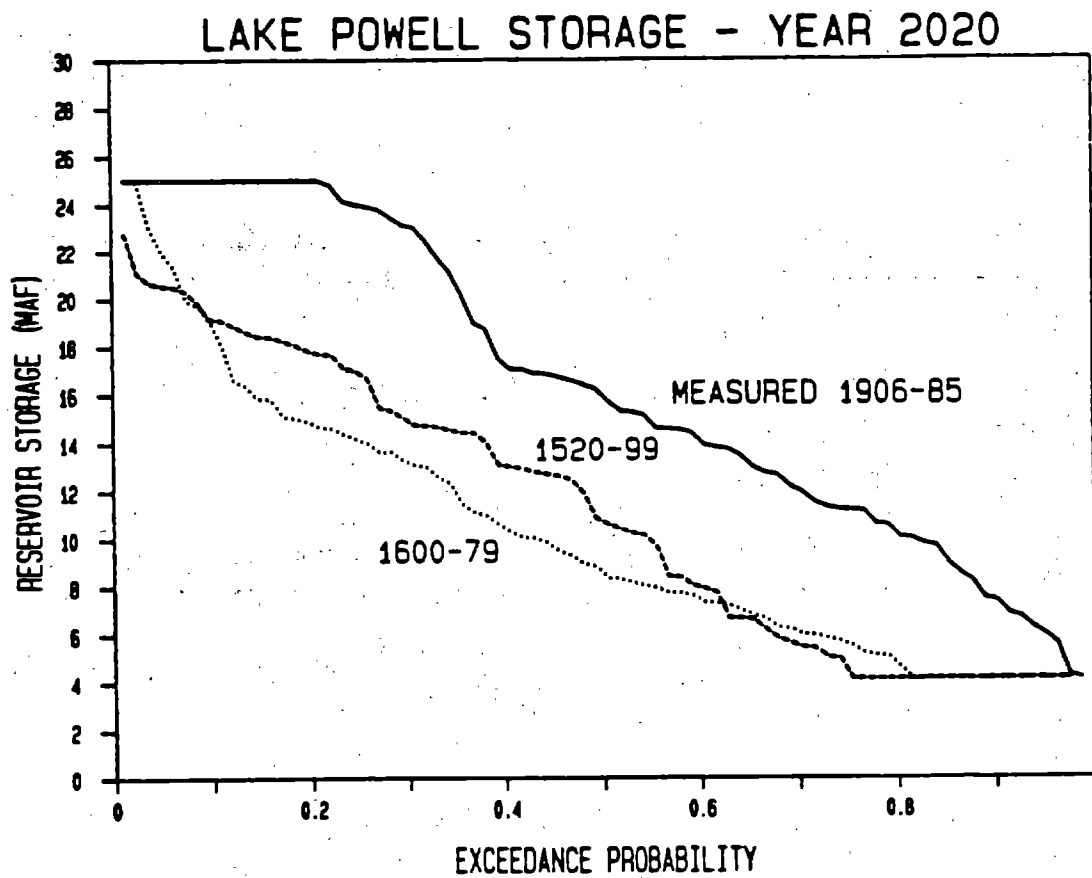
1600-79

RESERVOIR STORAGE (MAF)

EXCEEDANCE PROBABILITY

Figure 2-18. Lake Powell Storage CDF - Year 2020.

exhibit quite different types of droughts, preceding or subsequent high flow periods tended to produce an equalizing effect between them, when considering the entire 80-year sequence.

Lake Powell average storage levels were calculated by taking the average from 80 wrapped sequences for each simulation year. Results are shown in Figure 2-19. Note that the average storage level difference under severe sustained drought conditions ranges from approximately 5 to 6 maf from 1988 to 2020.

Lake Mead

Lake Mead simulation results are similar, with the difference between the base case and both drought sequences on the order of 6 maf for the year 2000 at 90% exceedence. Minimum power pool exceedence probabilities are about 80% and are shown in Figure 2-20. For the most severe drought scenario (1520-1599), minimum power pool exceedence levels decrease to about 50% by the year 2010, while those for the sequence 1600-1679 decrease to about 70% (see Figure 2-21). By simulation year 2020, these exceedence levels decrease to 40% and 55% respectively (see Figure 2-22). Minimum power pool exceedence predicted by the base case was greater than 95%.

Average storage levels for Lake Mead are shown in Figure 2-23, and indicate a maximum difference of about 6 maf between the base case and drought scenarios.

Upper Basin Shortages

Water shortages in the Upper Basin were allocated according to the interpretation of the Law of the River and storage provision requirements. Following the same procedure for the development of exceedence probabilities for reservoir storages similar cumulative distribution functions were developed for Upper Basin shortages. Year 2000 shortage probabilities are shown in Figure 2-24. The base case hydrologic sequence (1906-1985) indicates no shortages. The sequence 1520-1599 indicates shortages of about 300,000 acre-feet at the 75% exceedence level. The 1600-1679 sequence indicates Upper Basin shortages of about 300,000 acre-feet at about the 35% exceedence.

Shortages of about 300,000 acre-feet at the 95% and 87% exceedence levels are indicated by the year 2010 for the two drought sequences (see Figure 2-25). The base case sequence indicated no shortages. Similar results are shown for simulation year 2020 except
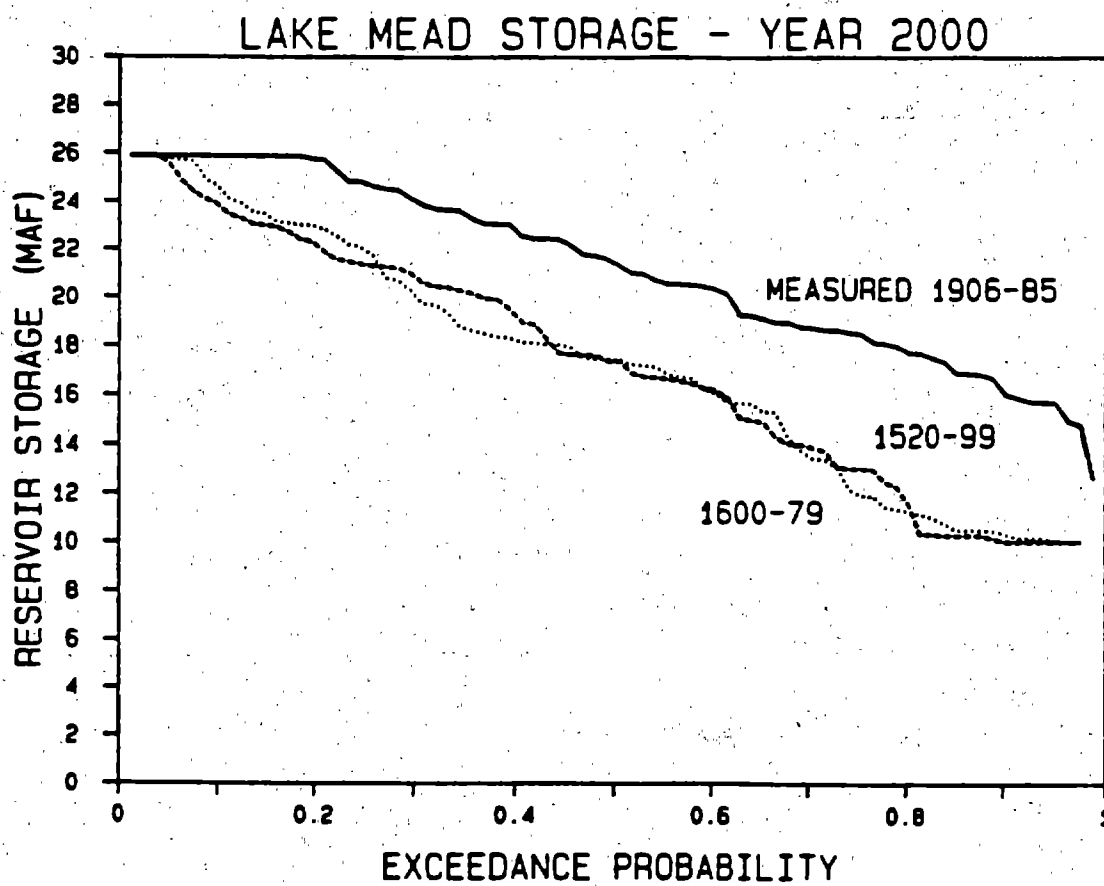
LAKE POWELL AVERAGE STORAGE
MEASURED AND TREE RING RECONSTRUCTIONS

(chart y-axis: RESERVOIR STORAGE (MAF); x-axis: DEMAND YEAR)

Labels on chart: MEASURED 1906-85, 1520-99, 1600-79
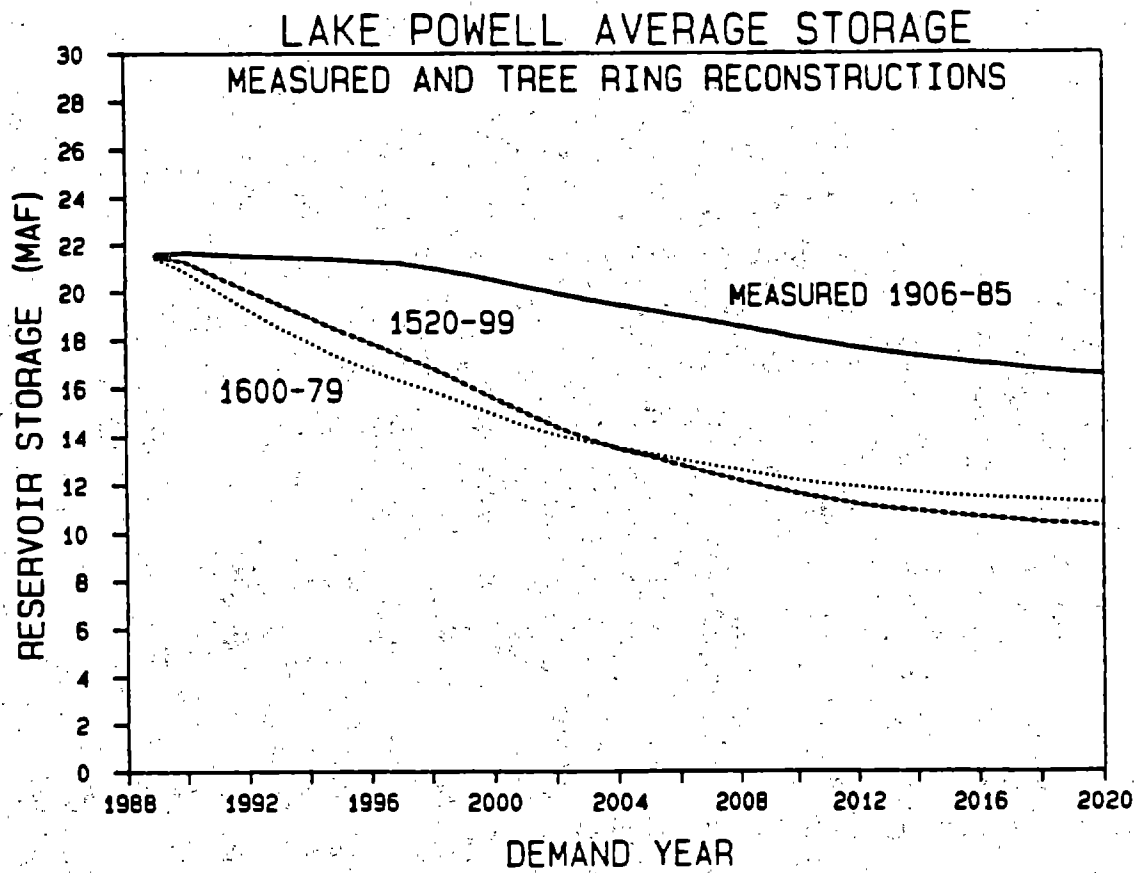
Figure 2-19. Lake Powell Average Storage Comparison.

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LAKE MEAD STORAGE – YEAR 2000

Figure 2-20. Lake Mead Storage CDF - Year 2000.

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LAKE MEAD STORAGE – YEAR 2010
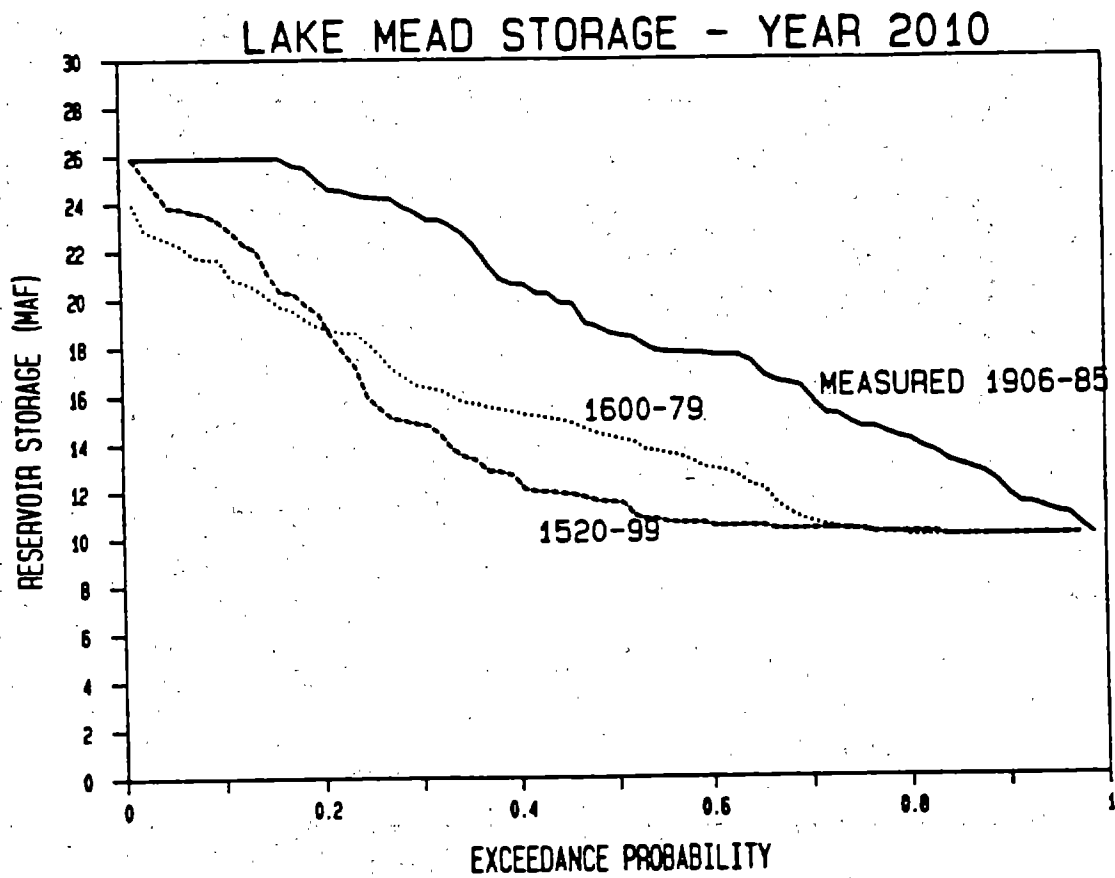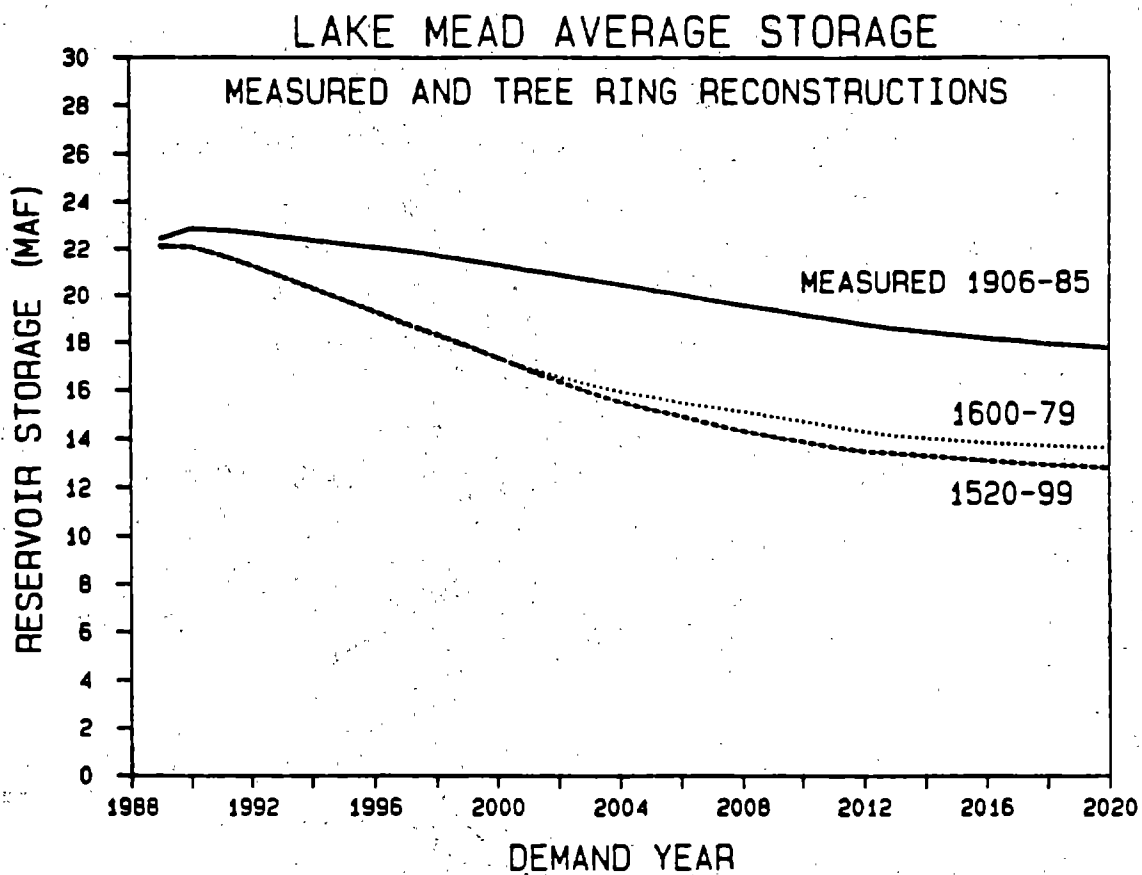
Figure 2-21. Lake Mead Storage CDF - Year 2010.

LAKE MEAD STORAGE – YEAR 2020

(chart axes: RESERVOIR STORAGE (MAF) on vertical axis from 0 to 30; EXCEEDANCE PROBABILITY on horizontal axis from 0 to 1)

Curve labels: MEASURED 1906-85, 1600-79, 1520-99
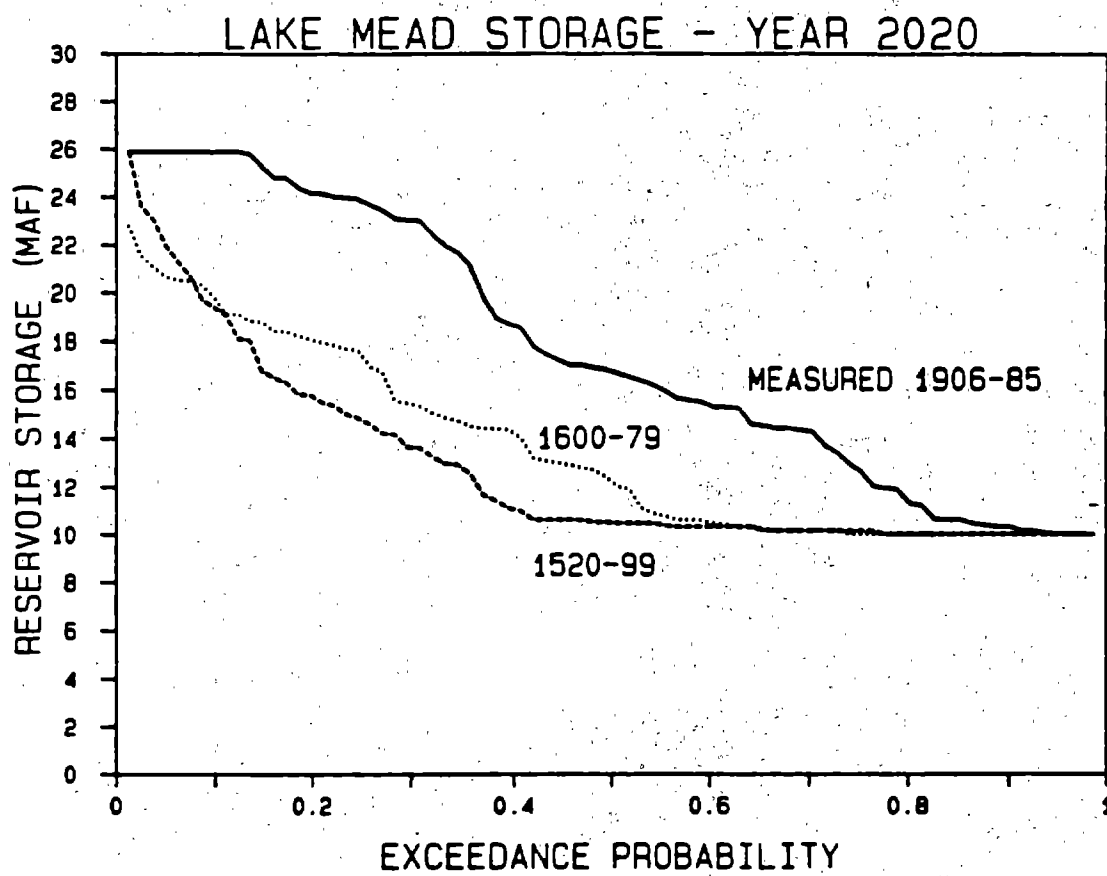
Figure 2-22. Lake Mead Storage CDF - Year 2020.

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LAKE MEAD AVERAGE STORAGE

MEASURED AND TREE RING RECONSTRUCTIONS

MEASURED 1906-85

1600-79

1520-99

Figure 2-23. Lake Mead Average Storage Comparison.

UPPER BASIN SHORTAGE - YEAR 2000
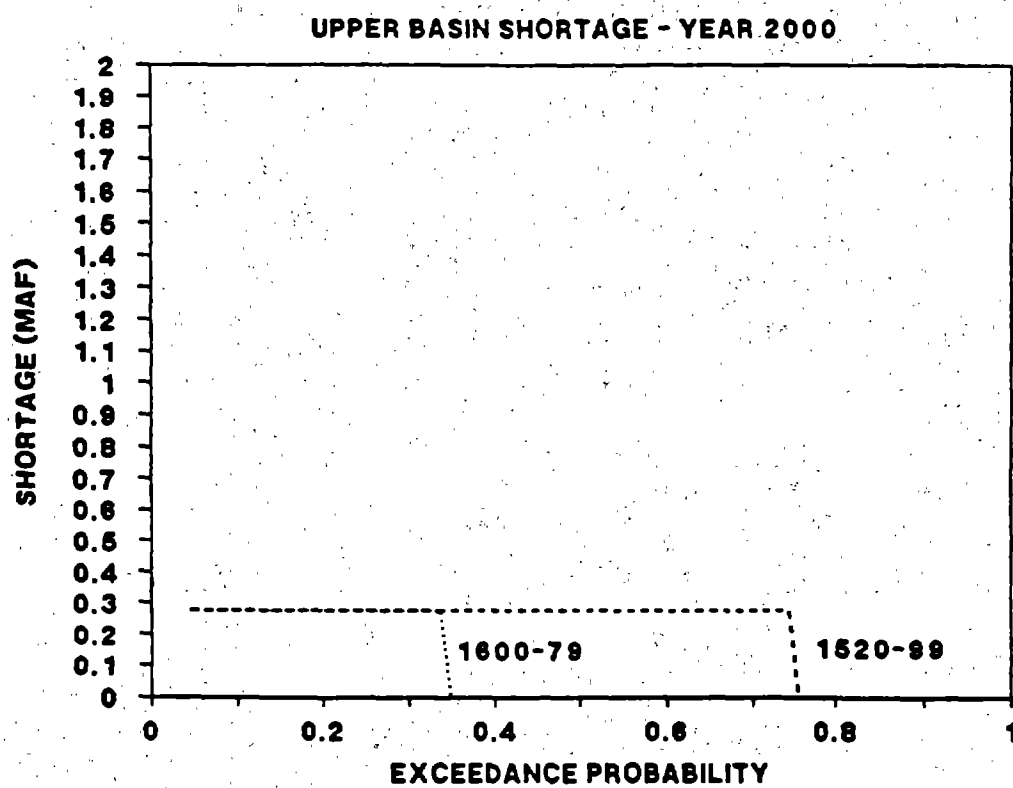
Figure 2-24. Upper Basin Shortage - Year 2000.

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UPPER BASIN SHORTAGE - YEAR 2010
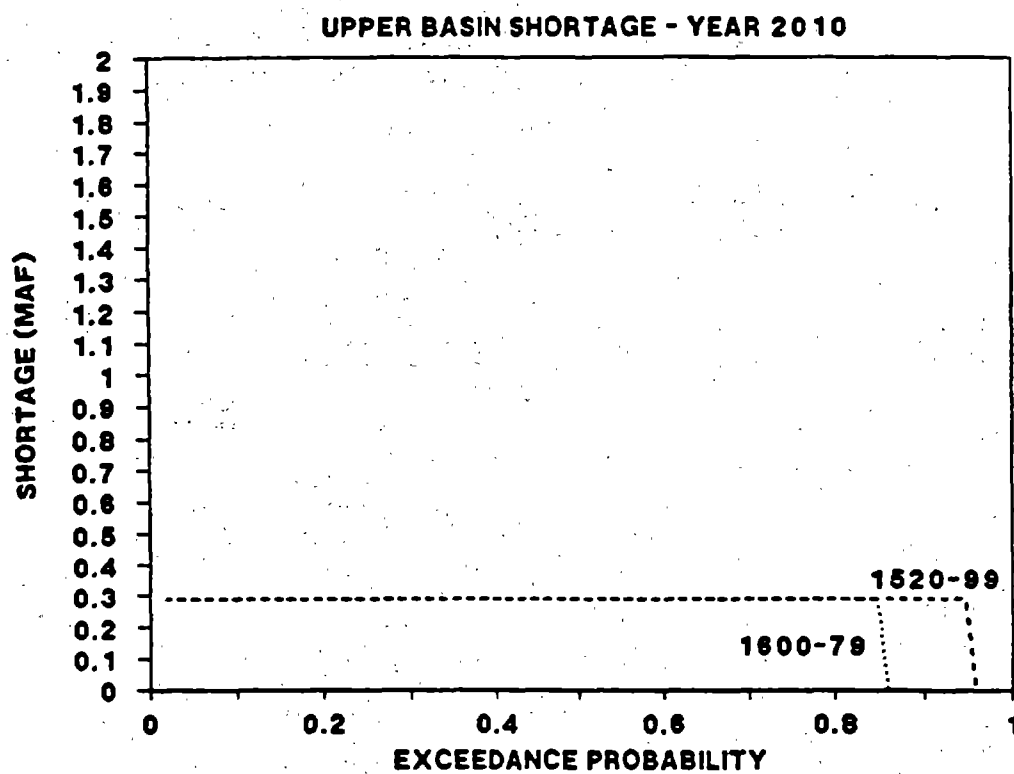
Figure 2-25. Upper Basin Shortage - Year 2010.

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that exceedence probabilities have increased in all cases, as shown in Figure 2-26. That is, shortages are present at the 98% and 88% exceedence levels for the two drought scenarios, while base case shortages are indicated at 50% exceedence. Average shortages for the 32-year simulation period are shown in Figure 2-27. Upper Basin shortages are shown as not exceeding 300,000 acre feet, consistent with prevailing U.S. Bureau of Reclamation operations policies.

Lower Basin Shortages

Calculated Lower Basin shortages were much more severe than those for the Upper Basin. For simulation year 2000, no shortages were predicted by the base case hydrology, although 1.45 maf shortages were calculated at the 70% and 30% exceedence levels for the drought sequences 1520-1599 and 1600-1679 respectively (see Figure 2-28). For the year 2010, the base case hydrology yielded 1.45 maf shortages at about the 50% exceedence level, while the 1520-1599 drought sequence showed the same shortages at 95% exceedence. The drought sequence 1600-1679 indicated 1.45 maf shortages at 85% exceedence, as shown in Figure 2-29. For simulation year 2020, the base case exceedence levels increase to about 60%, while the drought sequence 1520-1599 increases to greater than 98% exceedence. The period 1600-1679 yielded shortages at 85% exceedence, as shown in Figure 2-30.

Lower Basin average shortages are shown in Figure 2-31. The Lower Basin is expected to take the brunt of the severe shortages, with to the Upper Basin only being shorted 6%.

Conclusions

A repeat of the hydrologic periods 1520-1599 or 1600-1679 on the Colorado River would have significant impacts on water availability and shortage allocations in the Upper and Lower Basins. It should be noted that results presented here are not speculative what-if scenarios. For the most part, they represent likely outcomes of hydrologic sequences that *have taken place* in the recent past. Observation of Table 2-2 indicates that the river has had above-average flow (15.06 maf) over the past eighty years, as opposed to its previous average of about 13.5 maf per year. The potential for anthropogenic climatic change effects could exacerbate a situation where the equilibrium level of the Colorado River over the long term
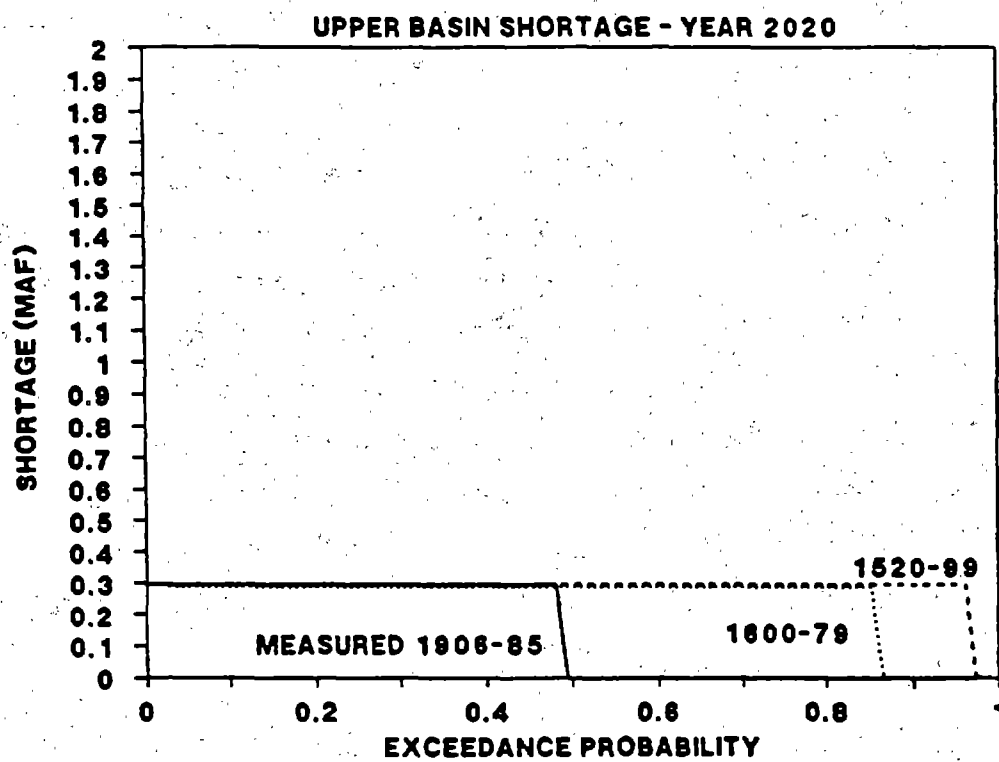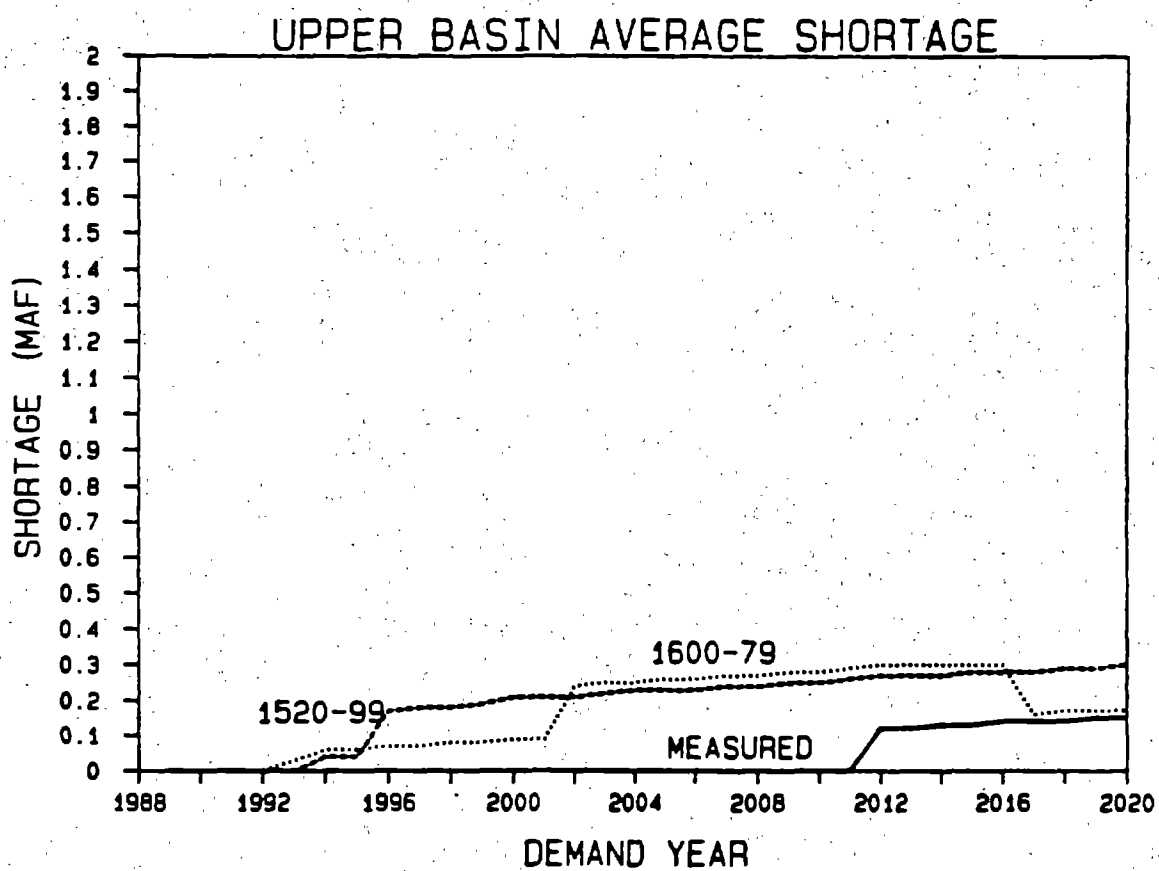
117

UPPER BASIN SHORTAGE - YEAR 2020

Figure 2-26. Upper Basin Shortage - Year 2020.

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Figure 2-27. Upper Basin Average Shortage.

LOWER BASIN SHORTAGE - YEAR 2000
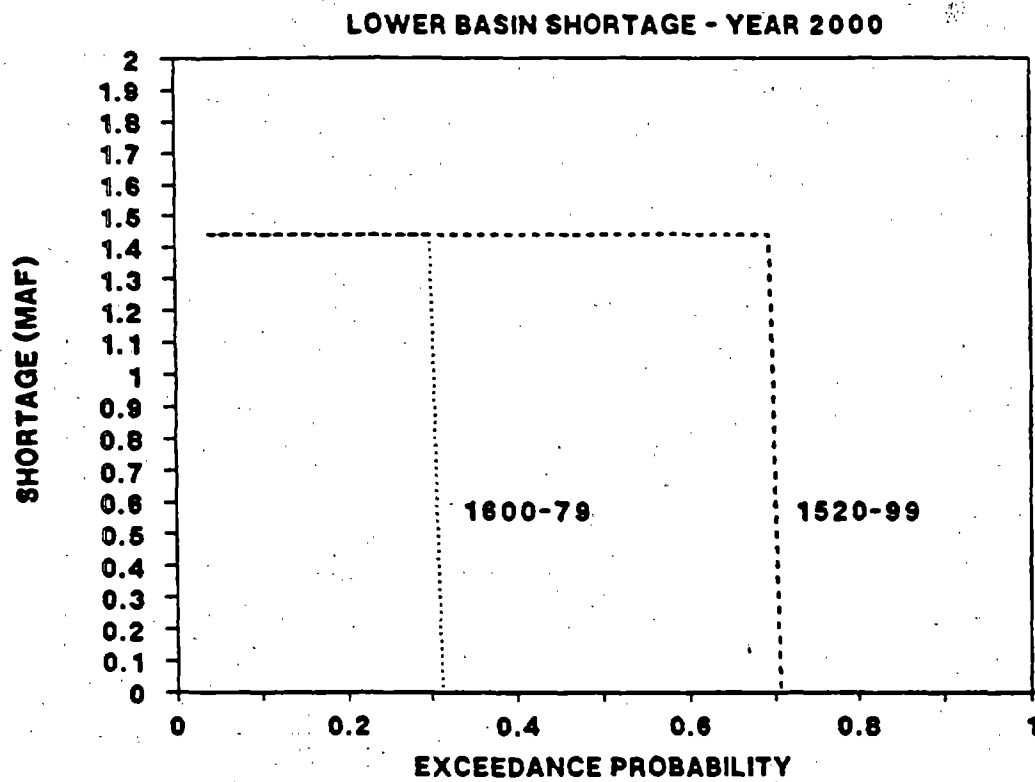
Figure 2-28. Lower Basin Shortage - Year 2000.

LOWER BASIN SHORTAGE - YEAR 2010
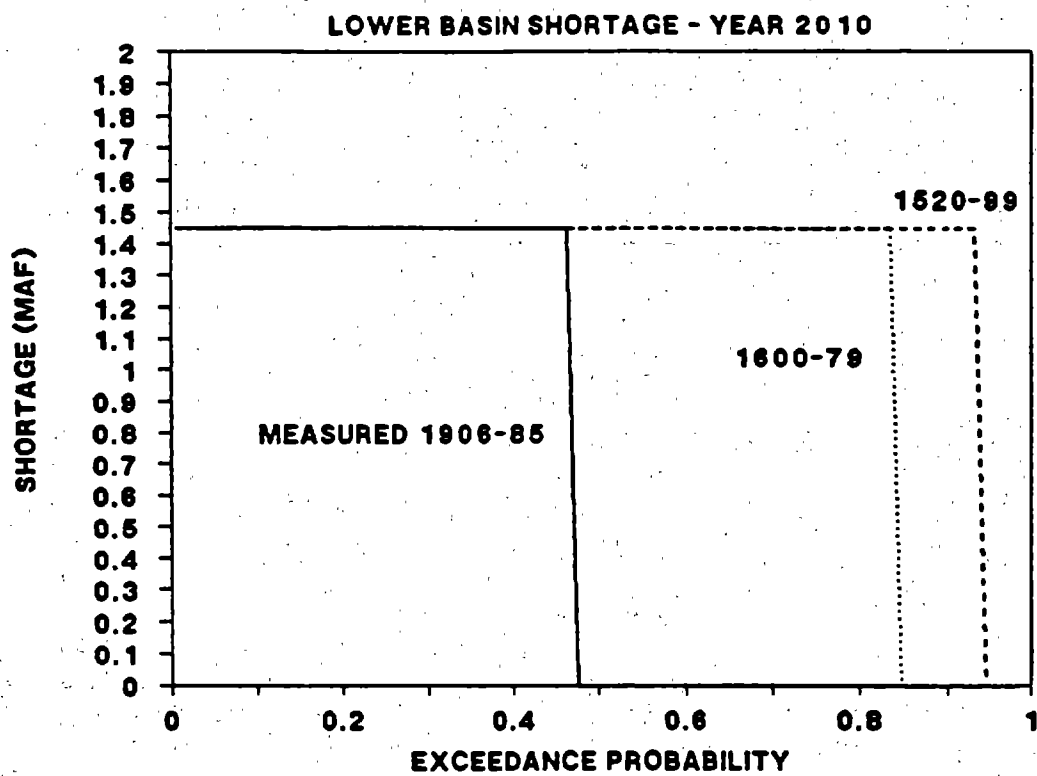
Figure 2-29. Lower Basin Shortage - Year 2010.

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Figure 2-30. Lower Basin Shortage - Year 2020.
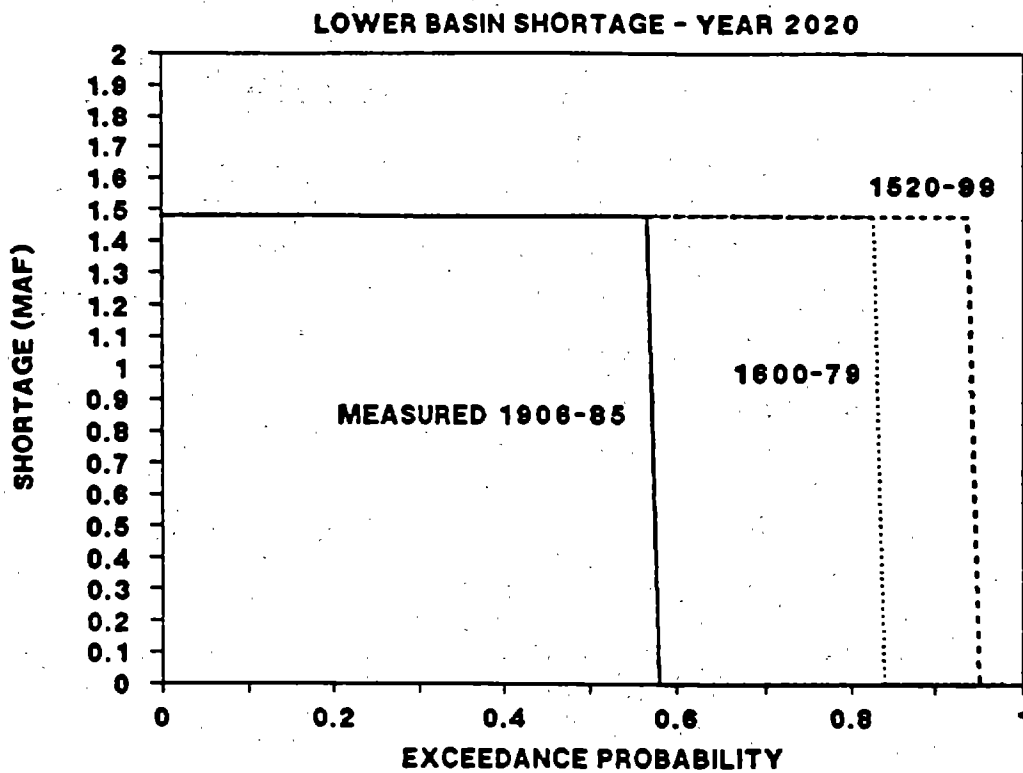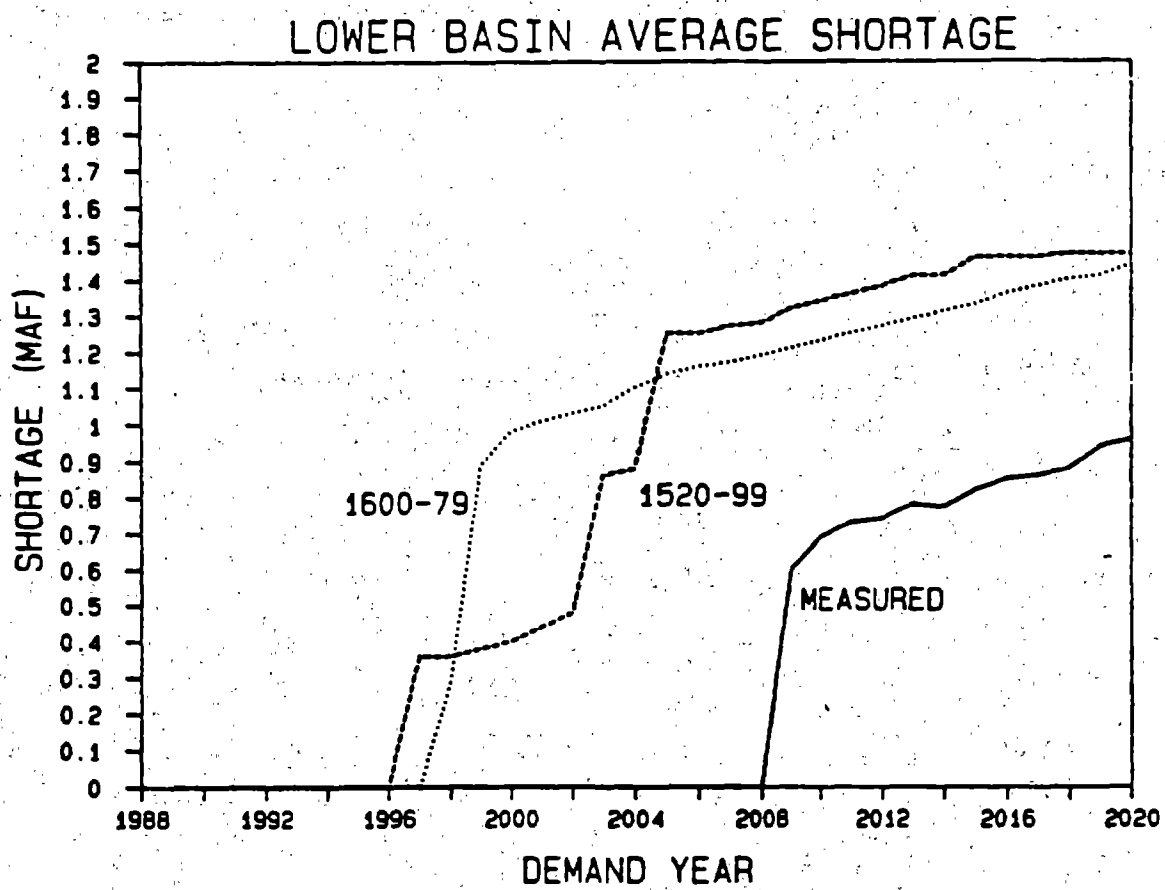
LOWER BASIN AVERAGE SHORTAGE

Figure 2-31. Lower Basin Average Shortage.

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(its mean flow) is lower than that measured over the past century. Shortages on the order of 300,000 acre-feet (under current system operation regimes) could occur in the Upper Basin as a result of hydrologic conditions derived from study of tree-ring data. Lower Basin shortages on the order of 1.5 maf have probabilities of occurrence of over 90% and about 85%, respectively, given the 1520-99 and 1600-79 droughts.

If the business-as-usual approach has been an optimistic one, then areas of future study need to focus on those activities that can help mitigate negative impacts in the Upper and Lower Colorado River Basins. These would include conservation practices, conservative management of surface and groundwater, and systems for orderly and mutually agreeable movement of water to higher-valued uses, including temporary transfers under drought conditions.

The merits of this study lie in the use of data drawn from events, not projections. While there is a degree of bias present in the tree-ring reconstructed sequences, its impact on water resources system analyses is currently unknown, and indeed may be small. Furthermore, estimates of the mean are considered to be reliable.

It is doubtful that Lake Powell and Lake Mead would be allowed to drop to minimum power pool levels before other types of shortage procedures were invoked, since in a real-time operation, there is no way to deduce ahead of time whether a drought has ended. This analysis distributes shortages in the Upper and Lower Basin in a manner that would be consistent with existing laws and operating criteria. By no means was it intended to be a statement of how shortages would in fact be allocated. Another area for future research is a critical assessment of potential shortage allocations and strategies that might be invoked by the Secretary of the Interior in the event of a severe and sustained drought.

It is in the area of politics that decisions will be made about ways of responding to, mitigating, and avoiding drought effects.

The Hurst Phenomenon

An assessment of severe and sustained drought would not be complete without a discussion of the hurst phenomenon and hydrologic persistence, which is the observed tendency of high flows to follow high flows, and low flows to follow low flows.

While studying the design capacity of reservoirs, Hurst (1950) came across an unexpected observation in the unimpaired hydrologic time series, namely persistence. He concentrated his research on a statistic called the "Range of Cumulative Departures from the Mean." This value is defined as

$$R_n = \sup S(i) - \inf S(j)$$

where $i = (0,1,...,n)$, and $j = (0,1,...,n)$, and where

$$S(k) = \sum_{i=1}^{k} (Q_i - E[Q])$$

for $k = 1,2,...,n$ where Q_i is the annual streamflow, and n is the sample size. The adjusted range is defined as

$$R_n^* = \sup S^*(i) - \inf S^*(j)$$

where

$$S^*(k) = \sum_{i=1}^{k} Q_i - \frac{k}{n} \sum_{i=1}^{n} Q_i$$

Q_i = water flow into reservoir in the ith year

$$\sum_{i=1}^{n} Q_i = \text{total inflow (n years)}$$

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$$\frac{1}{n} \sum_{i=1}^{n} Q_i = \text{average annual release}$$

$$\frac{k}{n} \sum_{i=1}^{n} Q_i \text{ amount released } (k \text{ years})$$

$S^*(k)$ = surplus or deficit relative to the amount released during the kth year and relative to the starting storage of the reservoir.

The difference between the largest surplus and the greatest deficit gives the capacity that a reservoir must have in order to maintain a constant release equal to the mean flow of the stream without overflows or deficits during the n-year period. From a design point of view, this concept holds merit only if it is assumed that flows in the future will replicate the historic flows. However, the statistical behavior of $R^*(n)$ can provide insight into the range of capacities that need to be maintained. Hurst investigated the behavior of a statistic called the "rescaled range," defined as $R^*/S(n)$, where $S(n)$ is the standard deviation of the sample of length n. He noted that the values of n versus $R^*(n)/S(n)$ plotted as straight lines on log-log graph paper. This indicates that the rescaled range follows an equation of the type

$$\frac{R^*(n)}{S(n)} = Kn^H$$

Hurst found that the average value for H was 0.73 with a standard deviation of 0.08. Feller (1951) pointed out that for a large n, a standard normal *independent* series behaves as

$$E[R^*(n)] = 1.25n^{0.5}$$

It would be expected that geophysical processes would typically be independent, which corresponds to an H of 0.5.

The tendency of hydrologic time series to produce values of H larger than 0.5 has become known as the Hurst Phenomenon, and H is known as the Hurst coefficient. It is an indicator of hydrologic persistence. A debate currently exists as to the significance of the Hurst phenomenon. There are three lines of thought.

1. The Hurst phenomenon is a transitory behavior. That is, existing streamflow records are simply not long enough to show the graduate shift to $n^{0.5}$. However, based on tree-ring data which yield a very long time series, Manelbrot and Wallis (1968) have argued against this idea.

2. The Hurst phenomenon is due to nonstationarities in the mean of the process. That is, there is a low frequency component in the mean which is slowly time-varying.

3. The Hurst phenomenon is due to stationary processes with very large memory. That is, the stationary processes have correlation functions which decay very slowly in time, much slower than Markov or autoregressive processes. In the limit, this is saying that natural processes have infinite memory. Physically, this is hard to justify.

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